Volume 20 JUNE, 1950 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

Ordovician diastems in Missouri ..... *E. Richard Larson* 63

General aspects of sedimentation in the geological basins of France ..... *André Vatan* 65

Inclusions in the quartz of igneous and metamorphic rocks. ..... *W. D. Keller, and Romaine F. Littlefield* 74

Mineralogy of some Cretaceous sandstones from the Colorado Front Range ..... *August Goldstein, Jr.* 85

Transportation of sediment by bubbles ..... *Henry W. Menard* 98

A sonic device for underwater sediment surveys ..... *E. C. LaFond, Robert S. Dietz, and J. A. Knauss* 107

Contorted Pleistocene strata at Newport Beach, California ..... *K. O. Emery* 111

A spot test for phosphorus in rocks ..... *Virgil I. Mann* 116

DISCUSSION

What is "sedimentology"? ..... *Marcus I. Goldman* 118

Journal of Sedimentary Petrology

W. H. TWENHOFEL, EDITOR
Orlando, Florida

J. L. HOUGH, Managing Editor
University of Illinois
Urbana, Illinois

ASSOCIATE EDITORS

W. C. KRUMBEIN
Evanston, Illinois

K. O. EMERY
University of Southern California
Los Angeles, California

HENRY B. MILNER
London, England

CLARENCE S. ROSS
Washington, D.C.

R. DANA RUSSELL
U. S. Navy Electronics Laboratory
University of California
San Diego, California

The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in March, June, September and December.

The subscription price of the *Journal of Sedimentary Petrology* is $5.00 per year prepaid to addresses in the United States.

Single numbers, $1.75 each ($1.35 to members).

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $5.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the *Journal*, subscriptions, rates, memberships, change of address, and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts, purely editorial matters, and advertising should be addressed to J. L. Hough, Journal of Sedimentary Petrology, University of Illinois, Urbana, Illinois.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

Volume 20 JUNE, 1950 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

CONTENTS

Ordovician diastems in Missouri.....*E. Richard Larson* 63

General aspects of sedimentation in the geological basins of France.....*André Vatan* 65

Inclusions in the quartz of igneous and metamorphic rocks.....*W. D. Keller and Romaine F. Littlefield* 74

Mineralogy of some Cretaceous sandstones from the Colorado Front Range.....*August Goldstein, Jr.* 85

Transportation of sediment by bubbles.....*Henry W. Menard* 98

A sonic device for underwater sediment surveys.....*E. C. LaFond, Robert S. Dietz, and J. A. Knauss* 107

Contorted Pleistocene strata at Newport Beach, California.....*K. O. Emery* 111

A spot test for phosphorus in rocks.....*Virgil I. Mann* 116

DISCUSSION

What is "sedimentology"?.....*Marcus I. Goldman* 118

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

ANNOUNCEMENT

The *Journal of Sedimentary Petrology* has been expanded, by vote of the Council of the Society of Economic Paleontologists and Mineralogists, and will be issued four times during the year. An increase in size of each issue to sixty-four pages has been authorized. This additional publication is provided at no additional cost to members of the society or to subscribers. The *Journal* will appear in March, June, September, and December. The current issue, dated June, 1950, initiates this schedule.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Initial shape and roundness of sedimentary rock mineral particles of sand size. By Harold L. Alling

The effect of continuous addition of mineral grains to a settling environment. By W. D. Lacabanne and G. A. Thiel

The petrology of a specimen of the Perry Farm shale. By W. D. Keller and Chuen Pu Ting

Removal of iron oxide coatings from mineral grains. By Carlton J. Leith

Sediment movement in relation to current velocity. By Henry W. Menard

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 63–64
JUNE, 1950

ORDOVICIAN DIASTEMS IN MISSOURI

E. RICHARD LARSON
University of Nevada, Reno, Nevada

ABSTRACT

Diastems are common features in the Plattin limestone (Middle Ordovician, Black River) in Missouri. Two prominent examples found by the writer in eastern Jefferson County are described. One is shown by the discordant molds of two large orthocone cephalopods, the second, more characteristic, by an intraformational conglomerate.

Convergence of the Plattin from Cape Girardeau to St. Louis County, Missouri is due to a reduction of the number of members and thinning of the members. Part of the thinning is attributed to frequent depositional hiatuses shown by diastems. The occurrence of closely spaced diastems in the Middle Ordovician in Central Pennsylvania is cited.

INTRODUCTION

Stratigraphic studies of the Plattin limestone (Middle Ordovician, Black River) in Missouri indicate that depositional hiatuses, marked by diastems, may be important factors in thickness reduction. Two conspicuous examples which the writer has found in the course of these studies are described. The first is shown by the molds of two large orthocone cephalopods. The second, an intraformational conglomerate, is more characteristic of other diastems found in the formation, but is conspicuous because of its thickness.

The diastems were found in a small, abandoned, "marble" quarry at the mouth of Prentiss Hollow, eastern Jefferson County. This locality is approximately 35 miles south of St. Louis in sec. 4, T. 39 N., R. 7 E.

Diastems, such as are found in the Plattin, are common features in the rocks of the more stable parts of the continents, but workers have seldom recorded their presence or indicated the significance of these intraformational structures. They are commonly marked by concentrations of fossils and intraformational conglomerates above a plane of removal, or by eroded fossils below such a plane.

DISCORDANT MOLDS

Internal molds of two orthocone cephalopods in the face of the Prentiss Hollow quarry called attention to the presence of a diastem. Closer examination showed that the break extends laterally across the quarry face.

Below the break is the mold of a large orthocone cephalopod, the upper portion of which has been eroded away (fig. 1). The mold is 9.4 cm in diameter and has an eccentric siphuncle and sutures 1 cm apart. The plane of removal coincides, approximately, with the diameter of the shell. This mold is formed of tan, lime mudstone containing gastropod fragments. Lying on the eroded surface of the mold, and with its long axis transverse to that of the first, is the mold of a large orthocone of elliptical cross section (fig. 1).

The material composing this second mold is also a tan, lime mudstone containing broken gastropod shells. It is transversed by irregular fucoid tubes, now filled by earthy material. The material forming the molds is similar to the surrounding rock matrix which is a pinkish tan, fucoidal lime mudstone, containing fragmental fossils.

The character of the molds and the

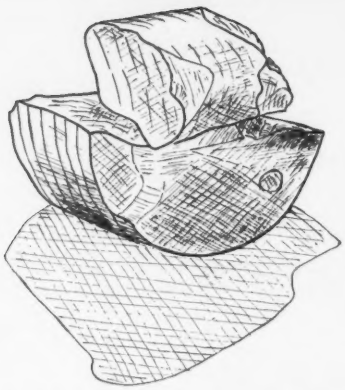


FIG. 1.—A diastem shown by cephalopods. The upper mold lies on a plane of removal which coincides, approximately, with the diameter of the lower shell.

nature of the surrounding rock indicate that the lower shell was buried in a lime mud which filtered into its interior. The presence of broken fossils suggests that the mud had undergone considerable agitation. Following the partial lithification of this material there was a depositional hiatus, during which the upper portion of the shell was eroded and the second shell settled on the new surface. Lime muds buried the second shell in this position. Reconstruction of the lower shell indicates that at least 5 cm of material was removed before the second shell was deposited in its present position.

INTRAFORMATIONAL CONGLOMERATES

A 15 cm bed of coarse intraformational conglomerate occurs at the lowest level of the quarry. This is made up of flat fragments of white-weathering, lime mudstone, up to 5 cm long, in a calcarenite matrix. These pebbles are the same material as the underlying and overlying beds. There is an upward gradation from laminated, white-weathering, lime mudstone, the laminae of which have been slightly disturbed, into conglomerate. The upper limit of the pebble bed is sharp. This conglomerate marks another hiatus during which the bottom sediments were agitated, although in this case little or no removal of material seems to have taken place.

STRATIGRAPHIC SIGNIFICANCE

Other parts of the Plattin show that hiatuses were frequent; intraformational conglomerates averaging 1 cm in thickness and slightly thicker shell beds marking diastems are abundant. These are only a few centimeters apart in some portions of the formation.

The Plattin thins northward from 400 feet at Cape Girardeau to 130 feet in St. Louis County, at distance of about 100 miles. This convergence is due to reduction of the number of members and thinning within members. At least a portion of the thinning of the members is attributed to the intraformational hiatuses shown by diastems.

Closely spaced intraformational conglomerates, marking diastems, have also been recorded by the writer (1947) in the Snyder and Stover limestones (Middle Ordovician) in Central Pennsylvania.

ACKNOWLEDGMENTS

I wish to acknowledge the assistance rendered by Dr. D. L. Frizzell, Missouri School of Mines and Metallurgy, Rolla, Missouri, in reading and criticizing this paper.

REFERENCE

LARSON, E. R., *1947*. Geology of Millheim Area, Center County, Pennsylvania: Unpublished master's thesis, Columbia University.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 65–73
FIGS. 1–2, JUNE, 1950

GENERAL ASPECTS OF SEDIMENTATION IN THE GEOLOGICAL BASINS OF FRANCE

ANDRÉ VATAN
French Petroleum Institute, Rueil (S. & Oise)

ABSTRACT

The three chief sedimentary basins of France (the Paris, Aquitanian, and Rhodanian Basins), and three smaller ones (Limagne, Forez, and Alsatian Basins), are defined.

The roles played by the marginal land areas are examined in each case. The primary importance of the Central Massif, and its progressive reduction during geological time, are demonstrated by heavy mineral methods.

Diastrophic influences on the sedimentary régimes are shown for the Aquitanian Basin (bordered on the south by the Pyrenees) and for the Rhodanian Basin (bordered on the east by the Alps). At different periods of time these two basins had comparable histories. Thus, during periods of orogenic quiescence Hercynian detritus predominated, whereas during periods of Pyrenean and Alpine orogenesis the sediment came chiefly from destruction of the young chains.

The mineralogical series discovered in the sediments reflect very closely successive stages of erosion of the land areas.

INTRODUCTION

One of the most striking geological features of France lies in the presence of three extensive sedimentary basins. These are: (1) the Paris Basin; (2) the Aquitanian Basin; (3) the Rhodanian Basin. Three smaller subsident basins also exist: the Alastian Basin and the Limagne and Forez basins (internal to the Central Massif and situated in the higher courses of the rivers Loire and Allier).

The petrological characters of the contained sediments vary regularly and systematically. The present paper is devoted to the description and interpretation of these arrangements.

In particular, the Central Massif is shown to have exerted a leading influence on the geological history of the French continental mainland. Situated in the center of France it is a vast inlier of ancient rocks, surrounded by younger sediments, forming the southern border of the Paris Basin, the northern border of the Aquitanian Basin and the western border of the Rhodanian Basin. The sedimentary histories of these three basins therefore run partially in step with the erosional history of the Central Massif. During non-orogenic periods the products of the Central Massif dominate in all three basins. During periods of Alpine and Pyrenean orogensis (whether embryonic or paroxysmal), however, the Rhodanian and Aquitanian basins received material from the new chains. The sedimentary histories of these two basins are, therefore, more complex than that of the Paris Basin, which throughout received only Hercynian material.

ACKNOWLEDGEMENTS

The writer is much indebted to Mr. P. Allen, Sedgwick Museum, Cambridge, for the complete revision of the original copy and many valuable suggestions and criticisms.

THE PARIS BASIN

Its Borders

The borders of the Paris Basin are well defined. To the west lies the Armorican Massif, to the south lies the Central Massif and to the east are the Vosges and Rhenish Massifs. The old Hercynian

chain shows greatly varied degrees of erosion from place to place.

In Brittany, the basement complex (mostly pre-Cambrain) comprises mainly low grade metamorphic rocks, chiefly sericitic slates and the like. Gneisses and schists are subordinate in amount. Granites invade the basement. Palaeozoic strata supervene over wide areas.

The Central Massif, on the other hand, has been more deeply eroded. Isometamorphic zones so far recognised (Roques, 1941) are as follows:

	Thickness (Approximate)
Non-metamorphic shale group	4,000 m
Mica-schists	
chlorite & muscovite zone..	3,000 m
biotite & muscovite zone...	3,000 m
Gneiss	
biotite & muscovite zone...	4,000 m
biotite zone.....	6,000 m

Staurolite and kyanite are characteristic minerals of the mica-schists. The staurolite includes a peculiar "vermicular" variety, which I have already described (Vatan, 1948, a). Cordierite and sillimanite (including its variety fibrolite) are typical minerals of the gneissic zones.

At the present day, the deep-seated gneisses and granites form the greater part of the outcrops in the Central Massif. Erosion has therefore occurred on a grand scale (see previous table). Its stages can be seen in the basins marginal to the Central Massif. Thus the dismantling of 6,000 m of mica-schist has given rise to the Mesozoic and Tertiary detrital sediments of the Paris Basin (and also, to a large extent, to the corresponding detrital sediments of the Aquitanian and Rhodanian Basins).

The Vosges Massif is still partially buried in Triassic (Vosgean) sandstone. The Ardennes-Rhenean Massif has similarly escaped deep dissection and, therefore, failed to contribute recognisable detrital materials.

Detrital Formations

Let us now examine the relationship between sedimentation in the Paris Basin and the concomitant erosion on its border. As continental formations usually provide the clearest possible evidence regarding detrital sources, attention will be confined mainly to these.

In the southern part of the Paris Basin, continental formations appear at the end of the Palaeozoic sequence and continue through to the Trias and infra-Lias. Their detritus came from the newly formed Hercynian chain. During the remainder of the Jurassic, a time of great transgression, the formation of calcareous marine sediments was preponderate. Detrital sediments reappear in the Cretaceous, but are only local in development.

Through the Tertiary, however, truly detrital sediments become progressively more frequent. Thus along the southern border of the basin, continental deposits of Sparnacian and upper Eocene age are known. They originated partly by direct erosion of the Central Massif and partly by removal of marine sands previously laid across the basin by transgressive Cretaceous seas. Northward they grade imperceptibly into marine beds.

Lacustrine sediments of upper Eocene and Oligocene age are also known. The center of sedimentation shifted laterally as the area of subsidence moved in time.

During the Miocene, the largely detrital "sables de l'Orléanais" and the Sologne sands were laid down. The former are calcareous and have yielded a vertebrate fauna; the latter are decalcified and unfossiliferous.

The Miocene closes with pebbly sands which pass through the Loire valley. Upstream, southward towards the high valleys of the Loire and Allier the sands link up with the detrital formations of northern Limagne and Forez. Downstream (westward) they connect with the "Faluns sea" (Helvetian), and thus were formed in an embayment extending from Normandy and the lower Loire to a point up the Loire valley just west of Orleans.

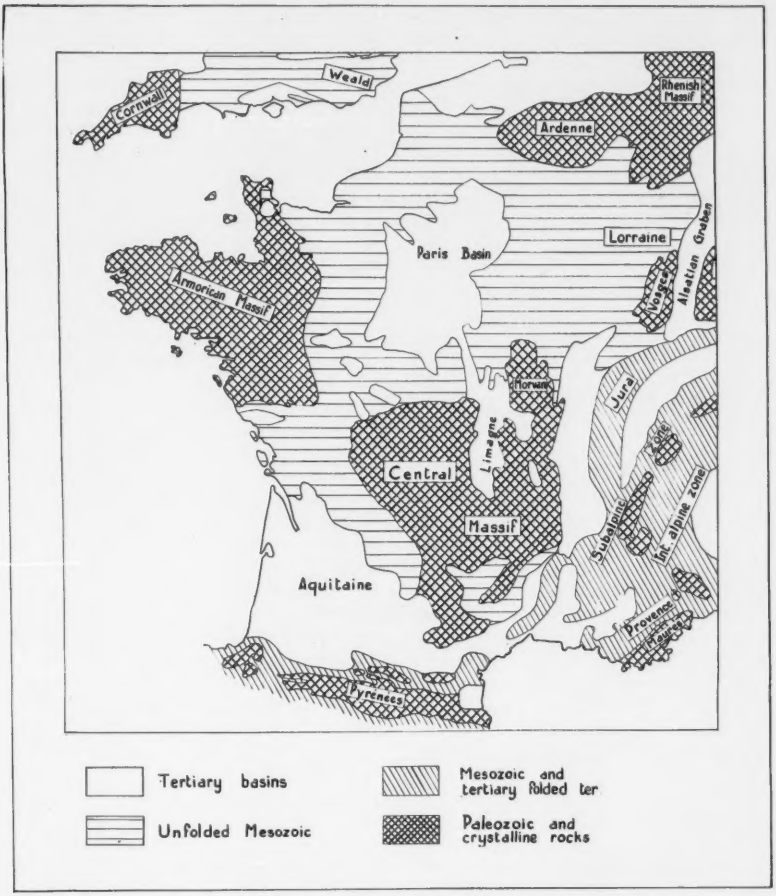


FIG. 1.—The geological basins of France.

Petrography

Sedimentation on the northern margin of the Central Massif was closely connected with the erosion of the ancient basement. The fundamental principle relating erosion and deposition was that of "inverted sedimentation," the newer sediments being deposited in the inverse order of the strata from which they originated. This principle was demonstrated by Bleicher in Alsace, where Oligocene deposits containing Jurassic boulders are followed successively by sediments first with Triassic and then with granitic boulders.

The principle is fully verified for the Paris Basin by detailed examination of the heavy minerals.

Continental Formations.—Carboniferous and Triassic continental rocks are

composed largely of granitic materials (derived from the Hercynian granites intruding Palaeozoic strata) and the superficially derived materials of general metamorphism (see table above). The continental upper Eocene beds, on the contrary, consist almost exclusively of minerals pertaining to the mica-schist zones (kyanite and staurolite) and the succeeding Miocene continental sands consist of minerals from the gneisses (sillimanite, fibrolite) and underlying granites (monazite, sphene). The Miocene sands also contain feldspars and small fragments of eruptive rocks of the granite series.

The above features enable the two last formations to be mapped with some precision, despite their unfossiliferous characters.

Marine Formations.—Detrital sedimentation began in the Anglo-Paris Basin with the Purbeck-Wealden and continued into the Albian (green sands and La Puysaye sands). On the southern borders of the basin, a detrital facies persisted through the Cenomanian, Turonian and Senonian. Since impact-marked boulders of Senonian rock occur in the Eocene, and must surely be marine in origin (Vatan, 1947), it is probable that littoral deposits of Upper Cretaceous age once largely covered the Central Massif.

The marine Tertiary formations of the Paris Basin are too well known to be worth recalling here. As their mineralogical composition is extremely constant, they may be considered to signify only local phases in the ebb and flow of the sea, representing but slight changes in paleogeography. Mineralogical distinctions between the various horizons are therefore difficult to establish. Correspondingly, the paleontological zones have no particular paleogeographical significance. This was made apparent by G. Brognon's recent researches on the Bartonian sands of the Paris Basin (Brognon, 1949).

The only characteristic feature of the Anglo-Parisian and Belgian sediments lies in the distinction between province B, the materials of which include the minerals of general metamorphism, and province A which includes minerals (e.g., hornblende) originating from the north. This discovery was made by Edelman (1947). The limits between the two provinces were recently determined in Belgium by Tavernier (1947). I may note incidentally that province B crosses at least part of southern England, for I recently came upon vermicular staurolite in the Aptian of Sandy (Bedfordshire), a small town 18 miles west-south-west of Cambridge. The limit between the provinces was probably mobile during the course of time. Doubtless the English geological school will soon enrich us with a detailed study of these fluctuations.

The heavy minerals are mostly metamorphic in origin (mica-schist zones). Kyanite is particularly abundant. Although the mica-schists of the Central Massif must certainly have intervened as "mother rocks" of the sediments, marine alluvial elements probably do occur therein. This opinion is based on the following argument: in certain modern estuaries (e.g., Rhine, Meuse, Seine) the rivers, having attained graded profiles, are now unable to carry their detritus to the sea. Marine sediments of diverse mineralogical composition are, therefore, transported and deposited far back in the estuary. The Helvetian "Faluns sea" of the central Loire valley appears to afford a further example of this. As already indicated, the gulf admitted a Miocene river carrying sediment which was dominantly gneissic and granitic in character. The sands of the "Faluns sea", however, while always containing these materials, also yield garnet (very seldom encountered in the continental sediments) and kyanite. The kyanite is a peculiar green-mottled variety quite unknown in the continental Miocene. Thus it is clear that, when seas are transgressive over epicontinental platforms, the erosive and carrying powers of the

rivers become considerably reduced due to the raising of their base-levels. On the other hand when base level lowers, usually tectonically, erosion increases and widely diversified continental formations then predominate in contrast to marine formations. Each of the different levels corresponds to a particular erosion stage of the Central Massif (Vatan, 1947, p. 186).

THE AQUITANIAN BASIN

Sedimentation in the Aquitanian Basin was the subject of a paper read by the author at the London International Congress (Vatan, 1948, b). I will therefore give here only a summary, plus a few complementary data, of the communication referred to.

Detrital sedimentation in the Aquitanian Basin is subject to rhythms determined by diastrophism. The Central Massif, which constitutes the northern limit of this basin, plays, as distributive province of the detrital material, a part inverse to that of the Pyrenees. Orogenic periods of the Pyrenees were characterized by intense erosion of the chain in course of formation and a concomitant sedimentation of their material. Materials originating from the Central Massif predominated during undisturbed periods. The study of the heavy mineral associations of these two provinces has afforded an accurate means of distinguishing between them.

The Central Massif, already deeply eroded in the Upper Cretaceous, contributed the minerals of general metamorphism from the zone of mica-schist (especially a vermicular variety of staurolite, and kyanite). The Pyrenees, on the contrary, were (and are) less eroded and provided mostly granitic contact materials (andalusite and garnet). The Upper Cretaceous (nascent orogenetic period: flysch) and particularly the Oligocene (major diastrophic phase: molasse) witnessed a predominance of Pyrenean material, whereas during the Eocene materials originating from the Central Massif (siderolithic sands without calcium) predominated, spreading far to the south, and these are now encountered in drillings below the Oligocene molasse.

Another difference between the Oligocene sediments and the Eocene sediments derived from the Central Massif (made known by M. Schoeller, 1941), reflects the variety of sedimentary conditions. The Eocene sediments, originating from a crystalline massif, were deposited in acidic waters with pH greater than 7, and contain no limestone. The Oligocene materials, on the contrary, were deposited under fluvio-lacustrine conditions in a base-level plain and are highly calcareous, at times even appearing in the form of lacustrine limestone.

The Aquitanian sediments formed by the dismantling of the Pyrenees have a total thickness of about 500 m. This represents the erosion of about 3,000 m of Pyrenean material.

THE RHODANIAN BASIN

While detrital sedimentation in Switzerland has been the subject of important studies by von Moos (1935) and Bersier, the petrology of the equivalent French materials has been dealt with only in two brief notes (Vatan and Journaux, 1949, and Vatan, 1949) and two local and older works (Deb, 1938, and Deverin, 1923).

The geological history of the Rhodanian Basin is very similar to that of the Aquitanian Basin. Again the sediments reflect exactly the formative processes of the Alps. During orogenically undisturbed periods sedimentation was controlled by the Hercynian chain of the Central Massif, but during orogenic movements of the Alpine chain, new sediments of noticeably Alpine character were formed. The growth of the Alps had, of course, already begun during the Trias, but only the Upper Cretaceous and later sediments are likely to provide sufficient mineralogical evidence for paleogeographical reconstructions.

As the basin lies along the eastern

flank of the Central Massif, the Middle and Upper Cretaceous deposits include detrital facies. During the upper Eocene the site of the Alps was occupied by a deep sea receiving nummulitic sands. Along the margin of the Central Massif, however, sandy continental formations were deposited, comparable to those of the same age found at the northern border of the Aquitanian Basin. These sands resulted largely from the reworking of former Cretaceous formations.

During the Oligocene, the Alpine sea tended to fill up and the Central Massif border became occupied by fluvio-lacustrine formations. From the beginning of the Miocene, however, the Alpine scene changed entirely and began to approach its present aspect. The emerged Alps were at first surrounded on the west and north by a shallow Perialpine sea receiving sediment (molasse[1]) derived from the destruction of the new chain.

[1] The etymology of the word "molasse" is somewhat controversial. It should be either *mollis*, meaning soft stone, or *moles*, meaning building stone. The Aquitanian molasse corresponds to the former meaning; the perialpine molasse to the latter.

Petrography.—The geological history outlined above is exactly reflected by the petrography of the sediments. The minerals in the Upper Cretaceous and upper Eocene indisuptably originated from the Central Massif, for they show the characteristic features enumerated above.

The first major mineralogical change occurs in the Oligocene and is progressive. Minerals resistant to chemical decomposition, zircon, tourmaline, rutile, occur in profusion, a fact denoting continental leaching conditions. Alpine minerals, though scanty, also begin to appear. Epidote and glaucophane are the most typical. These characterize the higher zones of general metamorphism, and they are practically absent (particularly glaucophane) from the Central Massif. Garnet, a mineral seldom encountered in the Central Massif, is also quite abundant.

The Alpine element appears in full force in the Miocene. Well-developed basal conglomerates contain many calcareous boulders of subalpine Upper Cretaceous rocks and also a few Jurassic radiolarites. Typical minerals are those

LEGEND FOR FIGURE 2

Diagram showing successive conditions at the northern margin of the Central Massif. Origin, transport and deposition of detrital materials are indicated.

I.—The northern border of the Central Massif at the stage of maximum erosion of the Hercynian chain.

The basement complex is represented—deep granites and the various zones of general metamorphism: gneiss, mica-schists, schists. The metamorphic formations are crossed here and there by intrusive granite. Only these intrusive granites and the metamorphic superstratum are affected.

II.—The southern margin of the Paris Basin during the Upper Cretaceous.

During the Jurassic, marine transgressions had resulted in the burial of the Central Massif beneath calcareous sediments, thus preserving it from erosion. During the Senonian, fresh detrital sediments extended southwards. Because of the high base-level, erosion of the Central Massif at that time was hardly appreciable. The resulting sediments are partly marine.

III.—The northern margin of the Central Massif and the southern part of the Paris Basin during the upper Eocene.

The base-level is now lower and erosion has increased, affecting the mica-schist zone. Cretaceous materials become reworked, the Senonian occurring as a remanié bed.

IV.—The northern margin of the Central Massif and the southern part of the Paris Basin during the Miocene.

After a temporary alleviation during the Oligocene (high base-level), erosion increases again during the Miocene. Gneiss and deep granites are denuded. Heavy minerals of these rocks appear: sillimanite, fibrolite, monazite, sphene, numerous feldspars and fragments of granite rocks. A Helvetian river flows along the Loire valley and into the Touraine "Faluns sea." Deposition of marine sediment derived from the west takes place (green-mottled kyanite, and garnet).

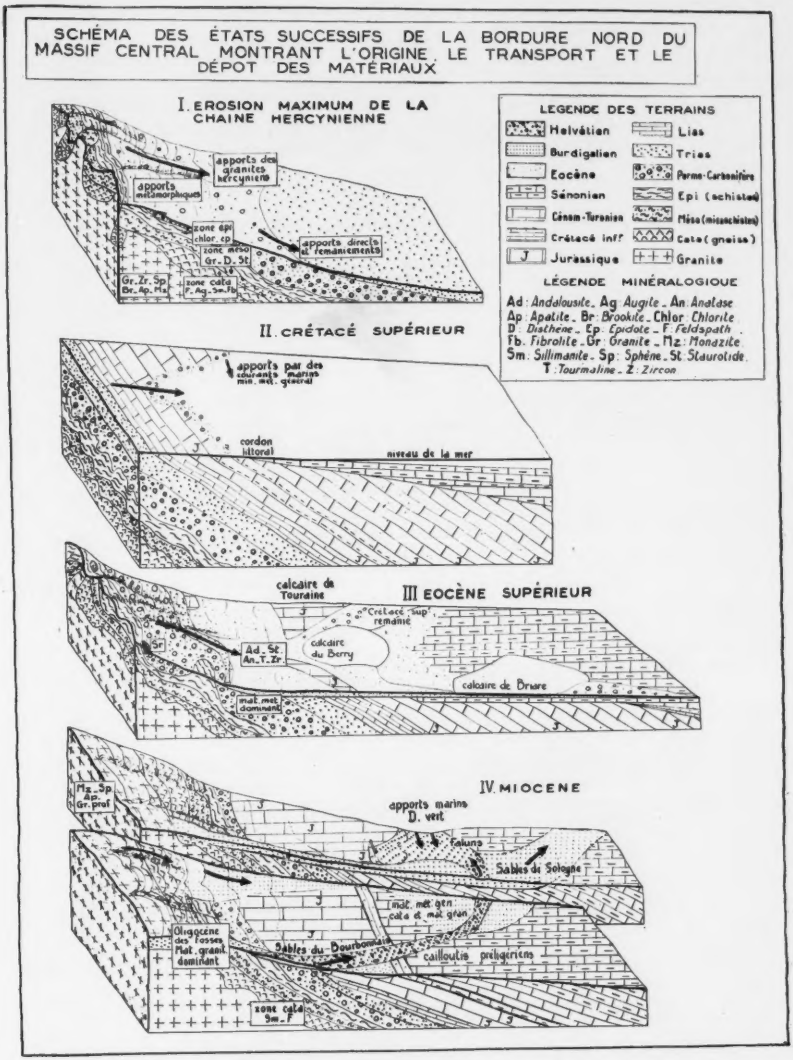


FIG. 2.—Successive conditions at the northern margin of the Central Massif.
Refer to Legend on opposite page.

of the Alpine province, glaucophane, epidote, garnet, and their profusion further increases in the Helvetian (Vatan, 1949).

Pliocene—As the Perialpine sea filled up with Alpine sediment, its geography became considerably modified. One marine transgression extended along a narrow gulf, as far as Givors. North of Lyons lay the Lake of Bresse. From previous researches and investigations made by General de Lamothe, R. Douville and G. Boyer, it was already known that certain pebbles between Besançon and Dole were, in fact, radiolarites of Alpine origin. In collaboration with A. Journaux we were recently able to confirm, by detailed study of the heavy minerals, the Alpine or possibly Rhenish character of the Lake de Bresse sediments. Materials originating from the Central Massif (staurolite and kyanite) were encountered, and the sediments must, therefore, be closely linked with the dismantling of the Cretaceous formations.

BASINS OF SUBSIDENCE

Limagne-Forez.—The Oligocene intra-Central Massif basins of subsidence contain a complex series of more or less lagoonal formations, arkoses, and marls-and-arkoses, overtopped by lacustrine formations. Laterites begin the succession in the Lembron region (south of Issoire). Detrital materials are local in occurrence and dominantly granitic in composition.

Alsace.—The Triassic Vosgean gritstones are, on the whole, fairly homogeneous and purely granitic in origin. The detrital material of the Alsatian Oligocene which I have been able to examine (from the Pechelbronn oil-basin) originated, in a proportion of at least 75 per cent, from the detrital cover of the Vosges. It is rich in fragments of phosphatised bone (Vatan, 1945).

CONCLUSION

Certain general observations may be drawn from this brief account of sedimentation in the French basins.

Erosion and sedimentation are closely allied phenomena. A clear notion of the metamorphic zones is indispensable to an understanding of the erosional histories of crystalline massifs. Sedimentary materials derived from the latter constitute statistical records of the chains as they existed at the time of deposition. In fact they operate as historical documents, which we, as the historians, have to interpret. Conversely, a knowledge of sedimentary petrography is indispensable to the worker on crystalline rocks, for a clear understanding of the processes of metamorphism.

The preponderating influence of orogenesis need not be reemphasized. Each mountain chain becomes flanked by its own detritus. From the moment of its formation, and even during the prenatal embryonic state, each chain is subejcted to erosion. The filling of sedimentary basins, therefore, reflects the tectonic episodes. Hence again, sedimentation provides, in a fossilized form, a cinematographic view of the mountain chain's constitution.

REFERENCES

ALIMEN, H., and VATAN A., *1937*. Contribution à l'étude pétrographique des sables stampiens: *Soc. géol. France Bull.*, 5ème série, t. VII, pp. 141–162.

BERGOUNIOUX, *1947*. Les terrains sidérolithiques du N. du Bassin d'Aquitaine: *Houille, Minerais, Pétrole*, March–April, pp. 47–51.

BERTHOIS, L., *1935*. Recherches sur les minéraux lourds des granites de la partie orientale du Massif amoricain: *Soc. géol. minéralogique Bretagne Mém.*, t. II.

BERTRAND, L., *1944*. Histoire géologique du sol français: 2 vol., 363 pp., 365 pp., Flammarion, Paris.

BRAJNIKOV, B., and DUPLAIX, *1943*. a) Quelques données et problèmes de lithologie sédimentaire dans le bassin parisien: *Soc. géol. France Bull.*, 5ème série, t. XIII, pp. 479–488. b) Sur l'origine des sables de l'estuaire de la Seine: *Comple rendu Ac. Sc.*, t. 217, pp. 572–574.

———, *1944*. Sur les associations de minéraux lourds de quelques rivières de la bordure S. du bassin de Paris: *Compte rendu Ac. Sc.*, t. 218, pp. 204–205.

BROGNON, G., *1949*. Minéralogie des sables bartoniens du bassin de Paris et de Belgique: *Soc. Belge de Géologie*.

CAYEUX, L., *1906*. Structure et origine des grès du tertiaire parisien—gites minéraux de la France.

———, *1916*. Introduction à l'étude pétrographique des roches sédimentaires: *Mém. carte géol. France*.

DEB, S., *1938*. Contribution à l'étude stratigraphique et pétrographique des roches tertiaires des Alpes-Maritimes: *Soc. géol. France Mém.*, t. XVI, fasc. I, no. 35.

DEVERIN, L., *1923*. Etude lithologique des roches crétacées des Alpes-Maritimes: *Serv. carte géol. France Bull.*

DUPLAIX, S., *1948*. Contribution à l'étude pétrographique des sables sparnaciens du bassin de Paris. *Soc. géol. France Bull.*, pp. 493–510.

EDELMAN, C. H., *1947*. La pétrologie des terrains tertiaires et quaternaires aux Pays-Bas: (Bibl.) La géologie des terrains récents, Sess, ext., *Soc. Belge de Géologie*, pp. 45–61.

GIGNOUX, M., *1945*. Géologie stratigraphique: 3d ed., Masson, Paris.

———, and MORET, L., *1945*. Géologie dauphinoise: 424 pp., Grenoble-Arthaud.

GUBLER, Y., and VATAN, A., *1943*. Rythmes de sédimentation dans le bassin de Nalzen (Ariège): *Soc. géol. France Bull.*, 5ème série, t. XIII, pp. 229–331.

GUILLIEN, Y., and VATAN, A., *1947*. Le remblaiement pliocène de la Basse Tardoire: *Revue Scientifique*, pp. 1051–1060.

JUNG, J., *1946*. L'Auvergne: *Mém. carte géol. France*.

MORET, L., *1947*. Précis de géologie: 637 pp., Masson, Paris.

ROQUES, M., *1941*. Les schistes cristallins de la partie SW du Massif Central français: *Mem. carte géol. France*.

SCHOELLER, H., *1941*. Etude sur le sidérolithique du Lot et du Lot-et-Garonne: *Serv. carte géol. France Bull.*, t. XLII, no. 206.

TAVERNIER, R., *1947*. Aperçu sur la pétrologie des terrains post paléozoïques de la Belgique: (Bibl.) La géologie des terrains récents, Sess, ext., *Soc. Belge de Géologie*, pp. 69–91.

VATAN, A., *1937*. Etude minéralogique comparée des sédiments arénacés du bassin de Paris: *Compte rendu Ac. Sc.*, t. 205, p. 70.

———, *1938*, Etude pétrographique des sédiments arénacés du Crétacé inf. dans le bassin de Paris méridional: *Soc. géol. France Bull.*, 5ème série, t. VIII, pp. 161–170.

———, *1945*. Etude minéralogique des provinces distributives du matériel sédimentaire d'Aquitaine: *Soc. géol. France Bull.*, 5ème série, t. XV, pp. 657–670.

———, *1946*. a) Remarques sur l'importance des remaniements: *Soc. géol. France Compte rendu*, pp. 204–205. b) Un exemple d'application des méthodes pétrographiques en paléogéographie; Les sables éocènes des petites Pyrénées: *Rev. Institut du Pétrole*, t. I, no. 2, pp. 89–96. c) Premiers résultats d'un examen pétrographique des matériaux sableux du bassin de Péchelbronn (B. R.): *Soc. géol. France Compte rendu*, p. 339.

———, *1947*. La sédimentation continentale tertiaire dans le bassin de Paris méridional: Paris Institut du Pétrole, 2, rue de Lubeck, 215 pp. 7 pls.

———, *1948*. a) La sédimentation détritique en Aquitaine aux temps tertiaires: *Soc. géol. France Compte rendu*, pp. 49–50. b) Rythmes de sédimentation en Aquitaine: Cong. Internat. Géol. Londres.

———, *1949*. La sédimentation détritique dans la zone subalpine: *Soc. géol. France Compte rendu*, pp. 102–104.

———, and FARCHAD, H., *1936*. Etude minéralogique des sédiments arénacés du Thanétien (Landenien marin): *Soc. géol. France Bull.*, 5ème série, t. VI, pp. 331–337.

———, and JOURNAUX, A., *1949*. Premiers résultats d'une étude pétrographique des matériaux des plaines de la Saône: *Soc. géol. France Compte rendu*, pp. 90–91.

VON MOOS, *1935*. a) Sediment petrographische unterschungen an Mollassesandstein: *Schweizer. min. pet. Mitt.*, bd. XV, pp. 169–265. b) Bohnherz, *ibid.*, bd. XVI, pp. 318–328.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 74–84
FIGS. 1–2, JUNE, 1950

INCLUSIONS IN THE QUARTZ OF IGNEOUS AND METAMORPHIC ROCKS

W. D. KELLER AND ROMAINE F. LITTLEFIELD
University of Missouri, Columbia, Missouri

ABSTRACT

The inclusions in the quartz from 35 igneous rocks and 16 metamorphic rocks were studied in detail in thin sections. They were grouped into "regular, acicular, globular, and irregular inclusions" following a modified scheme proposed by Mackie in 1896. In this study, regular inclusions characterize the quartz of schists, irregular inclusions predominate in igneous quartz, and globular and acicular inclusions are most abundant in igneous quartz although they also occur in metamorphic quartz.

Spectrographic analyses were run on 35 samples of petrogenic quartz. Even clear colorless quartz is rich in elements other than silicon and oxygen. Probably ordinary rock-forming minerals in sub-microscopically fine particles are abundantly included in most petrogenic quartz.

INTRODUCTION

Inclusions in crystals attracted interest as early as the first century when Pliny wrote about the "defects * * * and hidden humor within crystal." When petrographic microscopy was pioneered by Sorby, about 1858, new impetus was given to the study of very tiny inclusions. Later, Mackie studied the sands and sandstones of Eastern Moray (Scotland) and in 1896 concluded he could trace the provenance of the quartz sand by means of its inclusions. He stated as a "fairly general law" that certain inclusions abounded in the quartz of granite whereas other types of inclusions were more abundant in the quartz of gneiss and schistose rocks.

Mackie's findings are sufficiently important to merit an extension of his study to rocks of other localities. Numerous writers on sedimentary petrography have referred to and generally accepted Mackie's conclusions, but only one, to the authors' knowledge, studied the quartz of the probable source rock along with the sedimentary quartz. Tyler in 1936 related the St. Peter sandstone in Wisconsin to three granites, two gneisses, and two schists.

This paper reports on the abundance and varieties of inclusions in the quartz from 35 igneous rocks and 16 metamorphic rocks which were collected from scattered localities in the United States and Canada. Related observations on the appearance of the quartz, and spectrographic analyses of 35 samples are also included.

PREVIOUS WORK

Mackie (1899, p. 152) divided the inclusions he found in quartz grains into three classes and added a fourth class for quartz from which inclusions were absent as follows:

"I. Regular inclusions, and the quartz grains containing them, are classified as regular-inclusioned grains,

II. Acicular or fine needle-like inclusions and the grains showing these as acicular-inclusioned,

III. Irregular inclusions, giving an irregular-inclusioned group,

IV. Grains without inclusions, or where inclusions of the irregular type are so small as practically to escape notice.

Shortly, then we classify quartz grains, as regards inclusions, into Regular, Acicular, Irregular, None, for the sake of convenience, indicating the groups by the initial letters, R, A, I, N."

Among the "regular" inclusions Mackie listed: "quartz as an inclusion in quartz, chlorite, muscovite, biotite, rutile, apatite, zircon, garnet, magnetite, titaniferous iron." Presumably he included in the "regular" group those which were large enough to be identifiable and conventionally or regularly were rock-forming minerals.

Acicular inclusions were those which "appear as fine dark lines running in all directions through the quartz grains." The acicular group encompassed minerals which were not easy for Mackie to determine. The writers find similar difficulty, hence spectrochemical analyses not available in Mackie's time have been included.

"Irregular inclusions," according to Mackie, (1899, p. 154) "need no particular description. They are almost always fluid lacunae with or without gas bubbles. Various rocks are characterized by the presence or absence of gas bubbles in these fluid lacunae."

The point of dominant interest to the sedimentary petrographer lies in the possible diagnostic value of the inclusions as a means of differentiating the parent rock of quartz sand, whether igneous or metamorphic. In regard to this point Mackie wrote:

"Now it may be stated as a general law that acicular and irregular inclusions pre-eminently abound in the quartz of granite; that the regular group is to be found in various proportions, but always in relatively large numbers in the quartz of gneiss and the younger schistose rocks. * * * And here it may be well to state that where a grain contains two or more sets of inclusions, as not infrequently happens, the acicular have always taken precedence, and where they occur, though inclusions of other types have been present, the containing grain has been invariably registered 'Acicular'. Regular inclusions in the same manner have had precedence over the irregular variety. This it will be seen is simply a device to obviate cross classification."

Tyler (1936) "examined and counted the quartz grains, which contained the various types of inclusions, in three samples of granite, two gneisses, and two schists in order to check Mackie's general law." Tyler (1936) concluded: "It is evident that the three granite samples and the two schists check Mackie's general law. The gneisses, however, are characterized by irregular inclusions in the quartz, and thus should be classed with the granites rather than the metamorphic rocks. This suggests that perhaps regular inclusions are characteristic of paragneisses and schists and are not characteristic of the primary gneisses and schists. More detailed information is needed concerning the inclusions within the quartz of granites and metamorphic rocks before definite conclusions may be reached."

PROCEDURE

The quartz-bearing igneous and metamorphic rocks listed in table 1 were assembled from collections made by the junior author and augmented from other sources. Thin sections were prepared from 51 of them and the quartz studied petrographically; the quartz of the remainder was examined after crushing the rock.

The thin sections afforded a convenient way to study at length the quartz and its inclusions, and, therefore, a more detailed analysis of the inclusions was attempted than Mackie reported. As the study progressed it seemed logical to modify slightly Mackie's classification. First, the quartz from every specimen contained at least some inclusions and, therefore, Mackie's category IV, "None," was not used. Second, it is readily possible to differentiate with our modern microscopes the gas and liquid filled inclusions from other "irregular," tiny, indeterminable particles and "dust" inclusions. Consequently, in this report the globules of gas and liquid are called globules (G), and are separated from the remainder of the irregular inclusions which are placed in Mackie's "Irregular" group. "Acicular" and "Regular" are used in the same sense as in Mackie's

classification. The "Regular" inclusions are the large, identifiable, euhedral to anhedral petrogenic particles which appear to be included within other grains. It is realized that some of them are only apparent inclusions, appearing so when interlocking grains are sliced so as to leave part of one surrounded by another.

The abundance of inclusions in the quartz grains varied from none to large numbers in every quartz grain in a thin section. They were classified as "abundant (a)" if the variety of inclusion being described occurred in large numbers in all quartz grains in the section; "frequent (f)" if it occurred in all grains but notably less in some; "common (c)" if the inclusions were fairly well scattered, possibly absent in some of the quartz grains; and "rare" if they seldom were found after a careful examination of the section.

Regular inclusions.—The following minerals, listed in their approximate order of abundance, appeared to be included in the quartz: quartz within quartz, feldspar (both potash and plagioclase varieties), biotite, muscovite, magnetite, apatite, zircon, hornblende (rather rare), epidote, pyrite, riebeckite, aegerine, topaz, monazite (?), rutile (?), garnet (?), and hematite (fig. 1). Quartz within quartz may possibly be a true inclusion, or it may be a recrystallized portion, secondary quartz, or a projection of adjacent quartz which has been sliced in a fortuitous orientation during sectioning. Albite occurs more frequently as an inclusion than does orthoclase or microcline. Biotite is more abundant than muscovite, except possibly in schists. Zircon and apatite do not occur as inclusions in all sections, but are the most abundant of the accessory mineral group where they do occur. "Regular" inclusions are definitely more abundant in metamorphic than in igneous quartz.

Acicular inclusions.—Acicular inclusions range from none to abundant, and vary from about 0.04 mm to 1.5 mm in length, and are exceedingly fine. In some rocks the needles are aligned, in some they radiate from a center, and in others they occur in random orientation (fig. 2). It seems probable that one or more habits of acicular inclusions may characterize a particular rock occurrence and that acicular inclusions may be of critical importance in tracing the provenance of sand. More work with acicular inclusions may be fruitful of profitable returns.

Acicular minerals in metamorphic rocks are usually described in the literature as being sillimanite or kyanite. In igneous rocks they are usually referred to as rutile, less commonly as tourmaline. However, the spectrographic analyses run on the quartz studied showed less titanium and more boron than had been expected, hence the writers suspect that the reported abundance of rutile in rock-forming quartz may have been overrated. Riebeckite needles are also included in quartz as shown in the Quincy, Massachusetts, granite.

Globules.—Globules are very small, 0.001 to 0.01 mm in diameter, usually rounded to ellipsoidal inclusions. They may be scattered, but usually they occur in narrow to wide bands. The bands are visible using a 10× objective, but generally a 45× objective is necessary to resolve the individual globules. Many globules contain a tiny gas bubble which is in constant agitation due to Brownian movement.

The bands or streams of globules, actually probably sheets of globules, occur commonly in parallel alignment which may parallel possible crystal faces, growth zones, or shear planes. Bands of globules may pass across grain boundaries or through strained or recrystallized quartz. Some of them appear to continue into feldspar across the grain boundaries. Some bands are very straight; others are sinuous. Some are single-file lines; others are up to ten globules in width.

The variable and transgressive relationships suggest that the bands of globules were developed late in the crystallization (or recrystallization) history of the rock. Some are probably secondary.

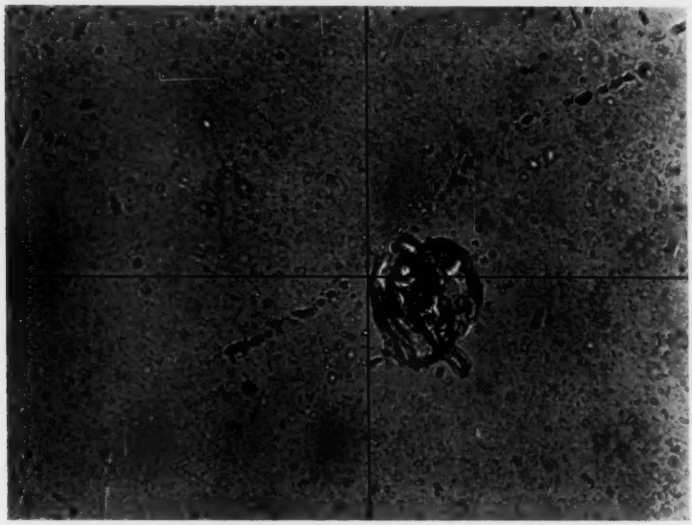


FIG. 1.—Photomicrograph showing globules and abundant irregular inclusions and one large regular inclusion in quartz phenocryst of rock no. 84, granite porphyry, Llano, Texas. Plain light, 200×.

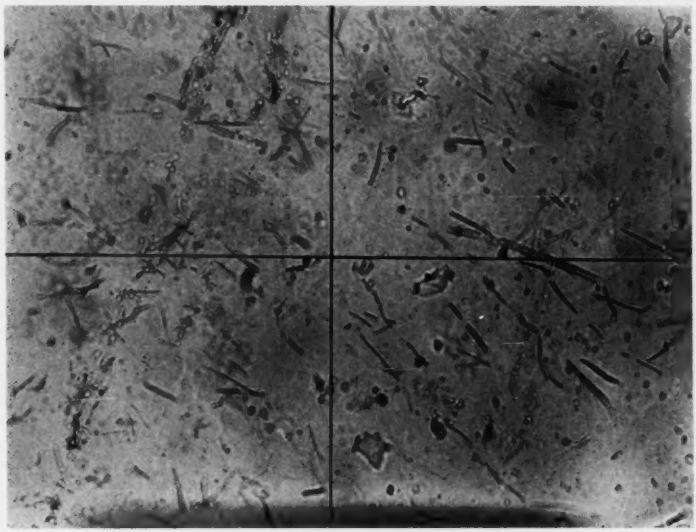


FIG. 2.—Photomicrograph showing short acicular inclusions in roughly parallel alignment, crossing bands of globules, granite no. 72, Lucerne, Maine. Plain light, 200×.

Globules are more abundant in igneous quartz than in metamorphic quartz, probably due to greater availability of fluids in the igneous system. Dale (1923) noted earlier the abundant sheets of cavities in the quartz of granite. Tarr and Neumann (1914) found the globules in the quartz of Missouri granite to be in sheets. Sorby (1858) associated the filling of the crystal cavities with the pressure-temperature environment during crystallization. Caution must be observed in this interpretation where cavities are secondary (Ingerson, 1947). Recently Scott (1948) has studied the decrepitation temperatures of ore minerals and quartz (personal communication, 1949), which may be related to the fluid inclusions.

The superficial survey made by the writers on single, spot hand specimens suggests that a careful and systematic study of the fluid inclusions in a body of igneous rock may contribute much to an understanding of its origin and history.

Irregular inclusions.—Irregular inclusions refer to very tiny, dark opaque "dust" particles in the quartz, and to tiny mineral flakes which resemble minute micaceous minerals. They are commonly associated with the bands of globules but are usually less abundant than the globules.

FREQUENCY OF VARIETIES OF INCLUSIONS

In table 1 are listed the rocks which were studied in thin section, their locality, the relative abundance of inclusions in their quartz, and the inclusion minerals identified. In order to present the complete and detailed data on the inclusions the table is necessarily lengthy. The data are summarized and condensed in table 2.

In table 2 are tabulated the frequencies with which each variety of inclusion occurs in the quartz of the phanerites and porphyritic aphanites, and in the gneisses and the schists. The data are further condensed by combining the very abundant, abundant, and frequent classes into one group, and the common, rare, very rare and none classes into another, and computing the percentage of the rocks which are so represented. These combinations are somewhat arbitary, but they represent a practical differentiation that could be made when examining the quartz of sandstone.

Reference to table 2 shows that igneous quartz is relatively free from large "regular" inclusions, but that the quartz of schist more likely contains them. Acicular inclusions are somewhat more abundant in igneous rock quartz. Globular inclusions are definitely more abundant

TABLE 1.—*The rock, type of inclusions and abundance of each in the quartz, the mineralogy of the inclusions, and the locality*

No.	Name	Minerals Present as Inclusions	Inclusions[1]				Locality
			R	A	G	I	
2	Granite	quartz, feldspar, biotite, apatite	r	f	a	f	Flagstaff, Mont. Boulder, Colo.
3	Gneissic granite	quartz, feldspar, muscovite, biotite	vr	n	r to c	f to a	Flagstaff, Mont. Boulder, Colo.
9	Granite	quartz, feldspar, biotite, magnetite (?)	c	c to f	a	f to a	Sinks Canyon, Lander, Wyo.
10	Granodiorite	quartz, feldspar, biotite, magnetite, apatite, hornblende	c	f	a	f to a	Sinks Canyon, Lander, Wyo.
15	Granite	quartz, feldspar, zircon, topaz (?)	r	n	a	f	Wind River, Canyon, Wyo.
17	Rhyolite porphyry	magnetite, apatite	r	n	r	c	Yellowstone Nat'l. Park, Wyo.
21	Hematite schist	magnetite (?), muscovite (?)	r	f to a	c	c	Atlantic City Area, Wyo.
22	Quartz-mica schist	muscovite, quartz	c	n	r (?)	f to a	Atlantic City Area, Wyo.
23	Granite gneiss	quartz, feldspar, biotite	r	n	f	f	Atlantic City Area, Wyo.

TABLE 1.—*Continued*

No.	Name	Minerals Present as Inclusions	Inclusions[1]				Locality
			R	A	G	I	
27	Granodiorite	quartz, feldspar, fibrous chlorite (?)	c	f	a	f	Road to Atlantic City, Wyo.
31	Granite	quartz, feldspar, biotite	r	vr	a	a	Sinks Canyon, Lander, Wyo.
39	Granodiorite	feldspar, biotite, magnetite, hornblende, zircon	r	vr	f	f	near Butte, Mont.
41	Granodiorite porphyry	feldspar, biotite, sphene, apatite, zircon (?)	r	n	f to a	f	near Bonners Ferry, Idaho
42	Granodiorite	quartz, feldspar, biotite, hornblende, magnetite, sphene	c	c	a	f	Careywood, Idaho
43	Granodiorite	quartz, feldspar, biotite	c	r	a	a	Grand Coulee Dam, Wash.
44	Gneissic granite	quartz, feldspar, biotite, zircon (?), iron oxide, apatite	c	n	f	f	Orondo, near Wenatchee, Wash.
45	Granodiorite	feldspar, biotite, magnetite, apatite, sphene, hornblende	c	r	f	f to a	Paradise Valley, Mt. Rainier, Wash.
50	Granodiorite	quartz, feldspar, biotite, sphene or zircon (?)	r	vr	f	f to a	Donner Pass, Calif.
52	Dacite	apatite, magnetite, zircon	r	r	c	f	Mt. Lassen, Calif.
53	Dacite	none	n	vr	f	f	Chaos Crag, Mt. Lassen, Calif.
54	Granite	quartz, feldspar, biotite	vr	r	a	a	Black Hills, S. D.
55	Granite gneiss	quartz, biotite (?)	vr	n	f to a	f	Little Belt Mountains, Mont.
57	Schist	feldspar, biotite, hematite, leucoxene	r	n	c	f	Wenatchee, Wash.
59	Quartz monzonite	quartz, biotite, apatite (?)	vr	c	c	f	Milford, N. H.
61	Granite	quartz, feldspar, biotite	r	f	a	a	North Jay, Me.
63	Granite	quartz, feldspar, biotite, fluorite (?)	r	f	a	f	Mt. Waldo, Me.
64	Granite	feldspar, biotite, hornblende, magnetite, epidote, zircon (?)	c	n	va	a	Franklin, Me.
65	Granite	quartz, feldspar, biotite, tourmaline (?)	r	n	a	f to a	Franklin, Me.
68	Graphic granite	feldspar, biotite	vr	n	a	f	Topeham, Me.
71	Granite	feldspar, biotite, magnetite, epidote (?)	r	r	va	a	Bar Harbor, Me.
72	Granite	quartz, feldspar, magnetite	r	a	a	f to a	Lucerne, Me.
73	Granite	riebeckite, aegerine, feldspar, magnetite, epidote	c	f to a	f	f	Quincy, Mass.
74	Rhyolite	biotite	vr	a	f	f	Machiasport, Me.
75	Gneiss	—	n	r	c	c	Belfast, Me.
76	Rhyolite porphyry	groundmass	r	n	f	f	Moosehead Lake, Me.
77	Schist	mica, graphite (?), zircon (?)	vr	n	f	c	Harpswell, Me.
78	Gneiss	quartz, biotite, zircon	r	n	f	f to a	Orrington, Me.
80	Rhyolite	—	n	n	c to f	r (?)	New Brunswick, Canada
82	Granite	quartz, biotite, feldspar, fluorite, magnetite, iron	c	n	a	f	Graniteville, Mo.
83	Granite	quartz, biotite, muscovite (?), pyrite	r to c	n	f	f	Barre, Vt.
84	Granite porphyry	groundmass, magnetite, apatite sphene (?)	r	va	a	f	Llano, Tex.
85	Granite	epidote, zircon	r	n	c	c	Ardmore, Okla.
86	Granodiorite	quartz, feldspar	r	r to c	f	f	Sierra Nevada Range, Calif.
88	Gneiss	feldspar, biotite, zircon, apatite	c	r	f to a	f	Rocky Mountain Nat'l. Park, Colo.
A255	Quartz, hornblende-biotite schist	biotite, hornblende	f	vr	r	r	Unknown
S273	Garnet gneiss	mica, chlorite (?), quartz, carbonate	r	r	f	f	Warren Co., N. Y.
S62	Sillimanite garnet	quartz, mica	r	r	f	r	Warren Co., N. Y.
A252	Garnet granite gneiss	feldspar, mica	r	vr	c	c	Unknown
S239	Quartz mica schist	quartz, mica	r	r	r	f	Unknown
S244	Quartz, muscovite schist	quartz, mica, feldspar	c	r	vr	r	Atlantic City, Wyo.
S247	Mica schist	mica, quartz	f	vr	vr	f	Unknown

[1] Key:
R refers to regular inclusion
A refers to acicular inclusion
G refers to globular inclusion
I refers to irregular inclusion

va refers to very abundant
a refers to abundant
f refers to frequent
c refers to common
r refers to rare
n refers to none

TABLE 2.—*Frequency of varieties of inclusions in the quartz of igneous and metamorphic rocks*[1]

Rocks	Inclusions																							
	Regular						Acicular						Globular						Irregular					
	a	f	c	r	vr	n	a	f	c	r	vr	n	a	f	c	r	vr	n	a	f	c	r	vr	n
Phanerites, 29			12	13	4		3	6	3	5	2	10	19	6	3	1			13	15	1			
Aphanite porphyries, 6				3	2	1	1			1	1	3		4	1	1				4	1	1		
Total igneous, 35			12	16	6	1	4	6	3	6	3	13	19	10	4	2			13	19	2	1		
Gneisses, 8			2	3	1	2				3	2	3	3	3	2					5	2	1		
Schists, 8		2	2	3	1		1			2	2	3		1	2	3	2		1	3	2	2		
Total metamorphic, 16		2	4	6	2	2	1			5	4	6	3	4	4	3	2		1	8	4	3		
	a–f		c–n				a–f		c–n				a–f		c–n				a–f		c–n			
Per cent in igneous quartz	0		100				29		71				83		17				91		9			
metamorphic quartz	12		88				6		94				44		56				56		44			

[1] Key: a = abundant, f = frequent, c = common, r = rare, n = none.

in igneous quartz than in that of schist. The quartz of gneiss carries inclusions similar to that of igneous rocks. Irregular inclusions are more abundant in igneous rock quartz than in that of either gneiss or schist.

The precision to which the percentages are reported is probably not justifiable on statistical grounds, but the data should indicate the trends of characteristic occurrences of inclusion varieties. We find our results to agree in general with those of Mackie, as shown in table 3.

APPLICATION TO DETERMINATION OF PROVENANCE

Although no one type of inclusion is diagnostic of either igneous or metamorphic quartz, it would follow from this study that a predominance of acicular and irregular inclusions in quartz (sand) would favor an igneous rock origin. Regular inclusions in notable abundance suggest a quartz-bearing schist as parent rock. Globular inclusions occur abundantly in the coarse quartz of granite and gneiss. Possibly the physicochemical environments of the two are similar and this is reflected in their quartz inclusions.

Agreement between Mackie's findings and those of the writers is close.

SPECTROGRAPHIC ANALYSES OF QUARTZ

With progressive examination of the inclusions in more and more quartz it was realized that many, perhaps most, of the inclusions were indeterminable by petrographic means with any appreciable degree of confidence. Spectrographic analyses were made of the quartz from

TABLE 3.—*Comparison of results from Mackie's and the writers' work*

Inclusions	Mackie	This paper
	Characterize:	Characterize:
Regular	Younger schistose rocks. Gneiss	Schists Not characteristic of gneiss
Irregular	Granite	Igneous rocks
Globular	Grouped with irregular inclusions	Igneous and gneiss
Acicular	Granite	Igneous rocks

22 of the rocks to give more information which might help in mineral identification. These analyses were augmented by 13 more on pegmatitic and vein quartz. The latter were chosen because the quartz was available in conveniently large particles (it is laborious to isolate "spectrographically clean" quartz from rocks), and also because very few spectrographic analyses have been published on any kind of petrogenic quartz.

The quartz for spectrographic analysis was separated from granites, etc., by crushing the rock between chalcedony cobbles (to avoid any chance of contamination by metallic crushing equipment), and then by picking out, with bone-tipped tweezers under a binocular microscope, relatively coarse quartz grains which were entirely free of adhering feldspar or other minerals. They were kept in glass vials until analyzed. Sieving, washing and pulverizing of the grains were avoided to eliminate any chance of picking up contaminating elements or of losing included volatiles.

The quartz was excited in the crater of a d. c. carbon arc at 40 volts and 10 amperes for one minute, using the cathode layer technique. A Jarrel-Ash 420 cm grating spectrograph was used. The spectrograms were compared with those taken from a wide range of known standard mixtures of silica and added elements. Some chance for error arises from uncontrollable variations in burn of the arc between different samples, and from the fact that the accessory elements in the standards are added in a different combination than the way they occur in the natural quartz. These possible defections are inherent in spectrographic technique even when performed in highly skilled hands.[1] The results are obviously semi-quantitative but should be accurate to within 50± per cent of the amount reported.

Potassium is present probably more frequently than reported because its minimum sensitivity is so high as to escape detection unless present in amounts greater than 0.01 per cent. Zirconium was not reported because its sensitive lines are masked by the cyanogen bands of the arc. An error was made in the copper standards resulting in erratic results and therefore copper is omitted from the report.

In table 4 are shown the quartz (rock) numbers and the spectrographic results. Below the chart, the rock numbers are identified, and a binocular microscope description given of the quartz fragments which were analyzed. The rock numbers which were described petrographically from thin section and reported on in table 1 are accompanied by an asterisk, as 9*.

It is obvious at first glance that clear, colorless quartz from igneous rocks is far from being pure SiO_2. Even crystal quartz of radio oscillator quality from Arkansas and Brazil (Frondel, 1945, p. 435) is likewise amazingly rich in elements other than silicon and oxygen.

With few exceptions the following elements were found in various amounts in every petrogenic quartz analyzed: Calcium, sodium, aluminum, magnesium, iron, manganese, and titanium. Less regularly were found also potassium, boron, barium, lead, strontium, zirconium, chromium, vanadium, zinc, lithium, copper, nickel, and cadmium, although a complete qualitative search for all the elements in the periodic table was not made.

It is reasonable to conclude from the spectrographic analyses that the following minerals are probably present as inclusions in petrogenic quartz: feldspar, as shown by the presence of calcium, sodium, and aluminum; biotite, as shown by magnesium, iron, and aluminum; amphibole and/or pyroxene, as shown by calcium, magnesium, iron, and aluminum; magnetite, by iron; and so on. If there is enough orthoclase, microcline, or possibly muscovite, potassium appears in the analysis. Similarly, titanium indi-

[1] Analyses were made by Dr. E. E. Pickett, Spectroscopist in charge of University of Missouri Spectrographic Laboratory.

TABLE 4.—*Spectrographic analyses of quartz; content of each element, expressed in per cent by weight, as found in the quartz*

Quartz No.	Ca	Na	Al	Mg	Fe	Mn	Ti	K	B	Ba	Pb	Sr	Cr	V	Zn	Li
6b	.005	.001	.03	.001	.03	.0003	.01									
9*	.5	1	1	.0005	.02	.0002	.01	.03		.1	.003	.05				
10*	.3	.2	.3	.003	.03	.001	.03									
16	.03	.01	.1	.001	.01		.003									
17*	3	3	3	.0003	.03	.0003	.03	.03		.3		.1				
26	.02	.001	.05	.005	.03		.002		.01			.03				
28	.05	.01	.05	.0003	.0003	.0001	.02									
30	.2	.03	.05	.002	.01	.002	.002									
35	.01	.001	.05	.0005	.003	.003										
40	.02	.01	.1	.001	.002		.01									t
41*	.03	.03	.05	.003	.03	.001	.05									t
45*	.1	.2	.1	.02	.1	.02	.1				.0003					t
50*	.05	.003	.001	.0005	.0001											
53*	1	1	3	.002	.03	.0005	.05			.05		.05				
54*	.02	.01	.05	.0003	.01	.0001	.001									
59*	.02	.003	.01	.00005	.0001											
60	.003	.01	.3	.005	.03	.003	.003									
61*	.3	.2	1	.003	.3	.01	.003			.03						
63*	.03	.05	.3	.00005	.02	.01										
65*	.1	.1	.3	.003	.02	.001	.01									
67		.001	.1	.0001	.0003	.0003	.005									
68*	.005	.03	.1	.0005	.003	.0005	.003									
69	.02	.01	.05	.0001	.003	.0001										
70	.03	.005	.5	.0002	.02	.0001										
71*	.05	.1	.2	.003	.1	.003	.05									
72*	.03	.03	.1	.001	.01	.002	.003									
73*	.01	.2	.3	.0003	.1	.001	.1									
82*	.05	.3	.5	.001	.05	.001	.003									
83*	.3	.5	.5	.003	.03	.0005	.005			.01	.0001				.003	
84*	.3	.2	.5	.003	.2	.01	.3		.005	.01					.01	
85*	.5	.05	.5	.01	.2	.001	.05					.03				
86*	.1	.01	.03	.0005	.003	.0001	.01									
87	.3	.05	.3	.1	.3	.0003	.03		.0003							
89	.03	.01	.05	.0002	.01	.0001										
90	.1	.01	.1	.002	.003	.001	.02		.0003							

No.	Quartz Source	Binocular Description
6b	Pegmatite, Virginia Dale, Colo.	Cloudy to milky quartz. Few inclusions. Slight iron oxide stain
9*	Granite, Sinks Canyon, Lander, Wyo.	Clear, colorless quartz. Feldspar, biotite, inclusions, slight iron oxide stain.
10*	Granodiorite, Sinks Canyon, Lander, Wyo.	Clear, colorless quartz. Minute biotite or hornblende inclusions.
16	Pegmatite, Owl Creek Mts., Wyo.	Clear, colorless quartz. No inclusions visible.
17*	Rhyolite porphyry, Yellowstone Nat. Park	Clear, Colorless to slightly yellowish quartz. Biotite (?) inclusion and rhyolitic coating.
26	Vein (gold) quartz, Atlantic City, Wyo.	Cloudy to smoky quartz. Black acicular inclusions in alignment.
28	Pegmatite, Sinks Canyon Road, Lander, Wyo.	Cloudy to colorless quartz. No inclusions visible.
30	Vein quartz, Atlantic City, Wyo.	Smoky quartz. Acicular inclusions. Slight iron oxide stain.
35	Pegmatite, Grand Teton Nat. Park	Clear, colorless quartz. Few tiny inclusions, slight iron oxide stain.
40	Granite, Troy, Idaho	Opaque, white quartz. Feldspar inclusions.
41*	Granodiorite porphyry, Bonners Ferry, Idaho	Clear, colorless quartz. Biotite (?), feldspar inclusions, slight iron oxide stain.
45*	Granodiorite, Mt. Rainier, Wash.	Clear, colorless to slightly smoky quartz. Tiny brown and black dust inclusions.
50*	Granodiorite, Donner Pass, Calif.	Clear to clouded quartz. Feldspar, biotite, and sphene or zircon (?) inclusions.
53*	Dacite, Chaos Crags, Mt. Lassen	Clear, colorless quartz. Slight coating by groundmass.
54*	Granite, Black Hills, S. Dak.	Clear, colorless quartz. Small black acicular inclusions. Slight iron oxide and feldspar coating
59*	Quartz monzonite, Milford, N. H.	Clear quartz. Few black biotite (?) inclusions.
60	Granite, Harvard, Mass.	Clear, colorless to slightly yellowish quartz. Slight iron oxide and feldspar strain.
61*	Granite, North Jay, Me.	Clear, colorless quartz. Tiny biotite inclusions.
63*	Granite, Mt. Waldo, Me.	Clear to light gray quartz. Biotite and feldspar inclusions.
65*	Granite, Franklin, Me.	Clear, colorless to light gray quartz. Biotite, hornblende (?), and feldspar inclusions.
67	Granetiferous pegmatite, Waldoboro, Me.	Clear to cloudy quartz.
68*	Graphic granite, Topsham, Me.	Clear to slightly yellow and smoky quartz. Few, very tiny "dust" inclusions.
69	Vein quartz, Topsham, Me.	Clear quartz with slight iron oxide stain.

TABLE 4.—*Continued*

No.	Quartz Source	Binocular Description
70	Quartz and tourmaline, Rumford, Me.	Clear, euhedral quartz crystals. Slight white to yellow coating.
71*	Granite, Bar Harbor, Me.	Clear, colorless to slightly gray quartz. Dusty, feldspar, hornblende, biotite inclusions
72*	Granite, Lucerne, Me.	Clear, colorless to slightly gray quartz. Few specks of biotite and feldspar.
73*	Granite, Quincy, Mass.	Clear to light gray quartz. Riebeckite and feldspar inclusions.
82*	Granite, Graniteville, Mo.	Clear, colorless to slightly gray and reddish quartz. Slight iron oxide stain, some black specks.
83*	Granite, Barret, Vt.	Clear, colorless quartz. Few small specks of biotite.
84*	Granite porphyry, Llano, Tex.	Sub-opaque, opalescent, bluish quartz. Few black inclusions.
85*	Granite, Ardmore, Okla.	Clear to slightly cloudy, colorless to yellowish green quartz. Few biotite (?) inclusions
86*	Granodiorite, Sierra Nevada Range	Clear, colorless quartz. Sparse, tiny biotite inclusions.
87	Granite, Estes Village, Colo.	Clear colorless quartz. Biotite inclusions. Slight iron oxide stain.
89	Pegmatitic granite, Black Hills, S. Dak.	Clear, colorless quartz. Sparse biotite (?) specks.
90	Vein quartz. Saganaga Lake, Ontario	Milky quartz. Tiny green specks and pyrite (?) inclusions.

Note. Detailed complete descriptions of all the specimens are recorded in a thesis submitted for the Master of Arts degree at the University of Missouri by the junior author: A Study of the Inclusions in the Quartz of Some Igneous and Metamorphic Rocks, 1949.

cates probably sphene, rutile, or ilmenite; and boron indicates probably tourmaline. It should be noted that barium, whose sensitivity limit is only 0.01 per cent, occurs in seven specimens. No barium-bearing mineral occurs commonly in granites, and it does not seem logical to assume that a rare mineral would occur as an inclusion in quartz in a number of granites when it does not occur megascopically. This is not consistent with the occurrence of other inclusions. However, barium is commonly isomorphous with calcium, and there are barium-bearing feldspars, so that it would seem to be a more logical assumption that the barium is present as a constituent of the feldspar which, in nearly all granites, occurs as inclusions. This same assumption could hold true for strontium, which is also in an isomorphous series with calcium, since it occurs in six specimens, commonly along with barium. The sensitivity limit for both barium and strontium is only 0.01 per cent and, therefore, it may be that they are of much more frequent occurrence in igneous rocks than has ordinarily been reported.

The occurrence of lead from three entirely different localities, granodiorite from Mt. Rainier, granite from Wyoming, and granite from Vermont, is interesting. In what isotope and why it occurs is not known.

A parallel relationship occurs between the number of inclusions present and the percentages of elements appearing in the analyses. Those quartz grains in which feldspar inclusions can be seen contained up to 3 per cent of calcium, sodium, and aluminum. On the other hand, quartz grains in which no inclusions could be seen under the binocular microscope contained approximately the same elements, but in much smaller amounts. Hence, one might assume that ordinary mineral inclusions below the limit of microscopic visibility are present. Perhaps the "irregular" dust particles are petrogenic mineral cyrstallites.

Because the titanium content does not seem to rise proportionately in the quartz rich in acicular inclusions, we suspect that needles in rock-forming quartz do not always mean rutile. Perhaps tourmaline, because of the boron found, is a significant acicular inclusion of petrogenic quartz.

One wonders to what extent other elements may proxy for silicon in the quartz crystal lattice, or to what extent infinitesimally small groupings, perhaps even a few unit cells, may have been absorbed or mechanically trapped during

crystallization.

A naive hope was entertained before beginning the spectrographic analyses that they would be simple and definitive of a few mineral possibilities. Actually the diverse sampling of quartz from many origins and ages has shown the complexity of composition, and breadth of possibilities in the non-silica portion of quartz. The problem merits a penetrating investigation of more restricted groups of quartz samples.

ACKNOWLEDGMENTS

Many specimens used in this study were donated by colleagues or were collected by members of the University of Missouri 1948 Summer Field Course. The expenses for running the spectrographical analyses were defrayed under University of Missouri Research Grant No. 320 (302). Dr. E. E. Pickett was especially helpful in connection with the spectrographic work.

REFERENCES

DALE, T. NELSON, *1923*. The commercial granites of New England: *U. S. Geol. Survey Bull.*, no. 738, pp. 1–473.

FRONDEL, CLIFFORD, *1945*. Effect of radiation on the elasticity of quartz: *Am. Mineralogist*, vol. 30, p. 435.

———, *1945*. Secondary dauphine twinning in quartz: *Am. Mineralogist*, vol. 30, pp. 447–460.

INGERSON, EARL, *1947*. Liquid inclusions in geologic thermometry: *Am. Mineralogist*, vol. 32, pp. 375–388.

MACKIE, WM., *1899*. The sands and sandstones of eastern Moray: *Edinburgh Geol. Soc. Trans.* VII, pp. 148–172.

SCOTT, H. S., *1948*. The decrepitation method applied to minerals with fluid inclusions: *Econ. Geology*, vol. 43, no. 8, pp. 637–654.

SORBY, H. C., *1858*. On the microscopical structure of crystals indicating the origin of minerals and rocks: *Geol. Soc. London Quart. Jour.*, vol. 14, pp. 453–500.

TARR, W. A., and NEUMAN, L. N., *1914*. A study of the effects of heat on Missouri granites: *Univ. of Missouri Bull.*, vol. 15, no. 27, 64 pp.

TYLER, STANLEY A., *1936*. Heavy minerals of the St. Peter Sandstone in Wisconsin: *Jour. Sedimentary Petrology*, vol. 6, pp. 72–77.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 85–97
FIGS. 1–4, JUNE, 1950

MINERALOGY OF SOME CRETACEOUS SANDSTONES FROM THE COLORADO FRONT RANGE

AUGUST GOLDSTEIN, JR.
3540 South Wheeling Avenue, Tulsa, Oklahoma

ABSTRACT

Heavy mineral suites of Cretaceous sandstones from the Colorado Front Range are described and discussed. Progressive variation in these suites between Dakota time and Laramie time is a function of the position of the sediment in the diastrophic cycle and results from addition of first-cycle sedimentary detritus in the early stages of the Laramide Revolution. A mineral stability series for Cretaceous sediments in the Front Range area is established.

INTRODUCTION

Fifty-one samples of Cretaceous sandstones of the Dakota, Fox Hills, and Laramie formations and the Hygiene sandstone member of the Pierre formation were analyzed for their heavy mineral content. Thin sections of representative samples were studied petrographically. Samples analyzed were collected along the Colorado Front Range from a few miles south of Morrison north to Soldier Canyon, near Fort Collins. (See fig. 1.)

At the beginning of the Upper Cretaceous, the Ancestral Rocky Mountains were very low and near base-level. The first sediments deposited on this Cretaceous "peneplain" were the conglomerates, sandstones, and shales of the Dakota group. The Dakota sediments are succeeded by the shales and limestones of the Colorado group (Benton, Niobrara, etc.). These fine-grained sediments were laid down in the slowly-sinking Cretaceous geosyncline. The geosyncline continued to sink throughout most of Montana time during the deposition of the black marine shales of the Pierre formation, interrupted by the Hygiene sandstone member in the middle Pierre.

Near the end of Montana time, the incipient destruction of the Cretaceous geosyncline in the Laramide Revolution is indicated by the deposition of the marine sandstones and sandy shales of the Fox Hills formation. These, in turn, were succeeded by the brackish and fresh-water sediments of the Laramie formation as the Cretaceous sea retreated from the Front Range area.

ACKNOWLEDGMENT

The writer wishes to acknowledge his indebtedness to members of the faculty of the Department of Geology of the University of Colorado, with whom these problems were discussed, and particularly to Mr. John R. Hayes, who collected many of the samples used in this study.

BASIC ASSUMPTIONS

In forming conclusions from the study of heavy mineral assemblages in the Front Range area, the following basic assumptions have been made:

1. *No major changes in drainage direction occurred between the rise of the Ancestral Rockies and the Laramide Revolution.* The Front Range element of the Ancestral Rockies may have centered west of the present Front Range, but it had an essentially north-south trend. Therefore, its major drainage was in an east-west direction. During the Mesozoic the sediments supplied to the present Front Range area were derived, for the most part, from the Ancestral Rockies on the west. The major drainage resulting from the uplift of the present Rocky Mountains is in an east-west direction.

As both of these ranges controlled drainage on the plains to their east, and as they had similar trends, the assumption that no major drainage changes occurred during the Mesozoic is considered to be justified.

2. *The pre-Cambrian complex of the Front Range area exposed to erosion by the Laramide Revolution in late Upper Cretaceous time was essentially the same terrane exposed by uplift of the Ancestral Rockies in late Pennsylvanian time. This pre-Cambrian complex has supplied a characteristic suite of heavy minerals to the sediments derived from it since late Pennsylvanian time. This suite, although impoverished in many deposits by elimination of its less resistant minerals, forms a recognizable entity in sediments throughout the Cretaceous.* Igneous activity in the Front Range area has been mostly restricted to the Tertiary and the pre-Cambrian. Between the Appalachian and Laramide Revolutions there was little intrusive activity in the Front Range area. Possible extrusive volcanism in southeastern Colorado in the Mesozoic seems to have contributed little to sediments of the Front Range. Therefore, the pre-Cambrian complex in late Pennsylvanian time was essentially the same terrane as at the end of the Cretaceous, and the first-cycle sediments eroded from this complex of igneous and metamorphic rocks at both times should have had essentially identical assemblages of heavy minerals. This characteristic assemblage of heavy minerals was being contributed to sediments of the Front Range area as long as the pre-Cambrian complex of either the Ancestral Rocky Mountains or the present Rocky Mountains was exposed. Furthermore, Tertiary igneous bodies form so small a part of the present Front Range distributive province (fig. 2) that the mineral assemblage being eroded off the present Front Range probably constitutes a close approximation to the first-cycle mineral assemblage of the Ancestral Rockies.

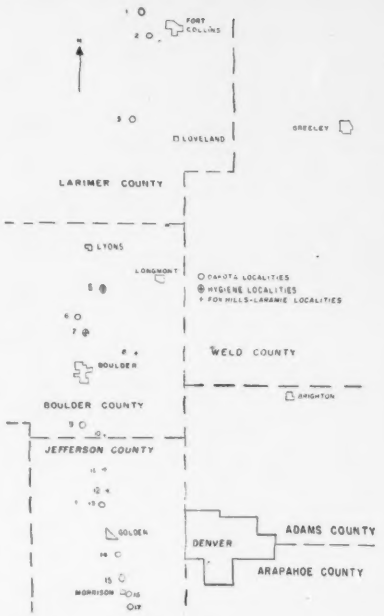


FIG. 1.—*Map showing localities from* which samples were collected for petrographic study.

Localities from which samples were collected for petrographic study and which are shown on map (Figure 1).

1. Soldier Canyon, sec. 7, T. 7 N., R. 69 W.
2. Spring Canyon, sec. 32, T. 7 N., R. 69 W.
3. NW¼ sec. 6, T. 5 N., R. 69 W.
4. Wildcat Mound, sec. 23, T. 4 N., R. 67 W.
5. Sec. 9, T. 2 N., R. 70 W.
6. NW¼SE¼ sec. 25, T. 2 N., R. 71 W.
7. Degge Mesa, sec. 6, T. 1 N., R. 70 W.
8. White Rocks, sec. 18, T. 1 N., R. 69 W.
9. Eldorado Springs, T. 1 S., R. 71 W.
10. Coal Creek, sec. 33, T. 1 S., R. 70 W.
11. Railroad cut north of Leyden Gulch, sec. 21, T. 2 S., R. 70 W.
12. Leyden Gulch, sec. 28, T. 2 S., R. 70 W.
13. Van Bibber Creek, T. 3 S., R. 70 W.
14. U. S. Highway 6-40 south of Golden, sec. 11, T. 4 S., R. 70 W.
15. West Alameda Parkway, sec. 26, T. 4 S., R. 70 W.
16. Bear Creek at Morrison, sec. 35, T. 4 S., R. 70 W.
17. Turkey Creek, NE¼ sec. 12, T. 5 S., R. 70 W.

LABORATORY METHODS

After disaggregating and drying each sample, it was shaken in a Ro-Tap sieve shaker for fifteen minutes and the heavy minerals then separated with bromoform. Owing to the paucity of heavy minerals

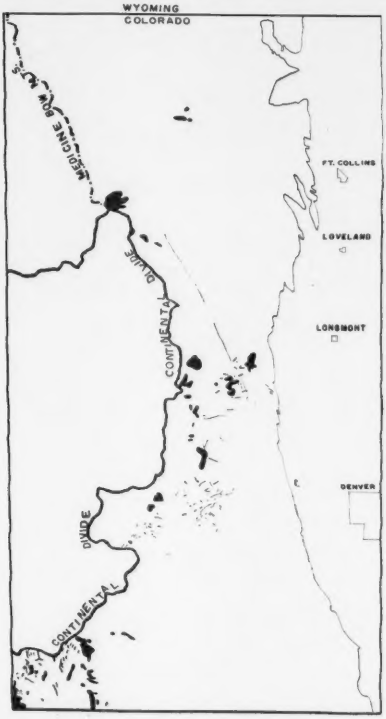


FIG. 2.—Map showing small areal extent of Tertiary igneous bodies in the Front Range distributive province. Thin continuous line at right is contact of sediments with the pre-Cambrian. Dark areas are Tertiary igneous bodies. Adapted from U. S. Geol. Survey geologic map of Colorado.

in the sandstones of the Dakota group, all of the sample passed by the 60-mesh[1] screen and retained on the 200-mesh[1] screen was used. With Hygiene, Fox Hills, and Laramie sandstones, the minus 100-mesh[1] to plus 200-mesh[1] size was used. After treatment with bromoform, washing with alcohol, and drying, the "magnetics" were removed with a horseshoe magnet and observed under a binocular microscope. The "heavies" were mounted in canada balsam and identified under a petrographic microscope. Heavy mineral counts were made by making several traverses across the slide with a mechanical stage. At least 300 grains were identified on each slide when more than 300 grains were present; when less than 300 grains were present, every grain was determined.

Limonite, hematite, and apatite were eliminated from those sandstones which were disaggregated by boiling with dilute HCl. Unidentifiable aggregates of several minerals and altered micaceous aggregates were not counted. Grains with widespread surface alteration were included only when they could be positively identified.

[1] Tyler screen sizes.

DAKOTA GROUP

Previous Studies

Very little published material is available on the heavy minerals of the Dakota group. Winchell (1936) reported:

> At Northwestern University Mr. Howard F. Miller has studied the Garo sandstone found in the Dakota hogback in South Park, Colorado. The restricted number of heavy accessory minerals (tourmaline, zircon, barite, garnet, muscovite, staurolite, chromite, and leucoxene) and their well-rounded character seem to indicate that the source of the sandstone was some pre-existing sedimentary formations rather than any nearby igneous rocks.

The Garo sandstone is now considered to be Jurassic and Miller's study may not be directly comparable to results of the present paper.

The mineralogy of the Cheyenne and Kiowa formations in Kansas was reported by Swineford and Williams (1945). The Cheyenne sandstone is approximately equivalent to the basal conglomerate and lower sandstone of the Dakota group in the Colorado Front Range, and the Kiowa formation is equivalent to the sandstones and shales of the middle part of the Dakota group. In both the Kiowa and Cheyenne formations, Swineford and Williams found an assemblage of heavy minerals consisting chiefly of zircon,

TABLE 1.—*Heavy mineral composition of sediments of the Dakota group*

Mineral Percentages	Sample Number																					
	D-8	D-10	D-12[1]	D-13	D-14[1]	D-17A	D-17B	D-17C	D-18	D-19[1]	D-21	D-23	D-24[1]	D-26[1]	D-27[1]	D-29[1]	D-39[1]	D-40[1]	D-41[1]	D-42	D-43
Ilmenite	9	11	4	10	6	28	5	7	6	12	3	4	4	5	6	12	20	6	6	19	16
Leucoxene	21	13	26	15	20	21	16	15	3	14	4	36	32	19	18	20	9	26	45	8	10
Tourmaline	18	9	7	2	4	1	6	24	4	18	3	12	24	11	12	6	3	17	26	6	8
Zircon	46	46	33	22	64	46	65	40	78	51	37	35	31	55	56	58	16	6	20	29	53
Staurolite	P	1	30	16	1		1	P		P		5	5	1	P		1		P	P	1
Garnet				P				P		P							5	1		3	
Rutile	1	2			2	P	2	2	8	P	P	P	P		1	P	1		2	1	
Titanite		1	P	4	1			2	1	1	P						4		1	P	P
Monazite					P	1				1	2	P				2					
Hornblende		1	1	3				1			P	P					23	38		7	
Actinolite-Tremolite																	4	2			
Epidote-Clinozoisite		P		1			P	P		P		P	P		1		6	2		1	P
Biotite	P	P		18				1		1	1	1		P			P		P	6	P
Muscovite		2		P		P	2	P	P	P	4	1	3	7	4	P		1	P	2	
Apatite				P		1		P									3			1	
Kyanite						P									1		3				
Limonite & Hematite	4	11		3		2	3	5	P		40	3								30	9
Pyrite		2		1	1	P				P	1		P			1	2	1			
Native Copper		P		3																	
Carbonates											3									P	

[1] Sample treated with HCl.
P—less than one per cent.

tourmaline, ilmenite, leucoxene, and garnet, with minor amounts of staurolite, titanite, hornblende, chlorite, rutile, barite and anatase. The only distinctive mineral ratio is that the amount of ilmenite exceeds the amount of leucoxene in most samples from the Cheyenne formation. In the "light" residue, muscovite is much more common in the Kiowa than in the Cheyenne. However, Swineford and Williams concluded that comparative mineralogy is useful only where it reflects the conditions under which the sand was deposited.

In Iowa, Tester (1931) found that the Dakota contains a mineral assemblage of quartz, glauconite, zircon, hornblende, tourmaline, muscovite, magnetite, leucoxene, pyrite, rarely ilmenite and garnet, a variety of feldspars, chlorite (?), sillimanite, quartzite, and iron oxide cement. Tester concluded:

> With the exception of the significance of the mineral glauconite in several of the sandstone zones of the type locality, a study of the mineral content of the sands yields very little information.*** The presence of a variety of minerals such as zircon, tourmaline, ilmenite, magnetite, and rutile means little as they occur in varying quantities at different localities and are generally distributed through sediments of different ages.

Description of Heavy Mineral Suite

The heavy minerals of sediments of the Dakota group are shown in table 1. The location of these samples is shown in table 2. A star diagram of the average heavy mineral composition is shown in figure 3. Any mineral which totaled one per cent or more of the heavy mineral composition in any single sample is included in the table of mineral composition. In addition, a few grains of each of the following minerals were found in Dakota sandstones:

Anatase
Cassiterite (?)
Sillimanite, var. fibrolite
Allanite
Basaltic hornblende
Barite
Galena
Martite (?)

Origin of Sediments

Heavy mineral assemblages indicate that the sediments of the Dakota group were derived from a complex source terrane and that a long period of time in-

TABLE 2.—*Location of samples of Dakota sandstones used in heavy mineral studies*

Locality No.	Stratigraphic Position	Sample No.
2	Basal conglomerate	D-21
3	Basal conglomerate	D-42
9	Basal conglomerate	D-39
	Middle sandstone	D-41
	Upper sandstone	D-40
13	Middle sandstone	D-8
	Top of middle sandstone	D-43
	Upper sandstone	D-10
15	Base of lower sandstone	D-23
	Top of lower sandstone	D-24
	Sandstone from middle of lower shale section	D-26
	Sandstone from top of lower shale section	D-27
16	Basal sandstone at Morrison contact	D-17 A
	Two feet above D-17 A	D-17 B
	Two feet above D-17 B	D-17 C
	Middle sandstone	D-18
	Base of upper sandstone	D-19
17	Basal conglomerate	D-12
	Lower sandstone	D-13
	Middle sandstone	D-14

tervened between their erosion from the parent rock and their final deposition. Rounding of grains is, for the most part, a function of particle size and the larger detrital particles are typically well-rounded. Krynine (1946) divided tourmalines into thirteen types and found that certain types were typical of certain source rocks. For example, indicolite is typical of pegmatites. All of these types are present in Dakota sandstones.

On the basis of the criteria established by Krynine (1943) and Pettijohn (1949, p. 242) the sandstones of the Dakota group are "first-cycle" orthoquartzites. However, it seems probable that a considerable part of the detritus of which the sandstones of the Dakota group are composed was derived from pre-existing sediments. Two factors suggestive of this origin are:

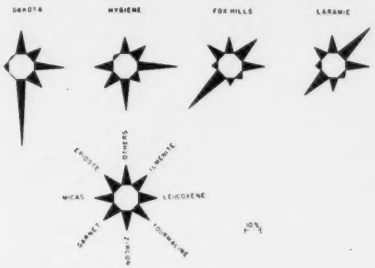


FIG. 3.—Star diagrams of average heavy mineral composition of some Upper Cretaceous sandstones from the Colorado Front Range.

1. Predominance of tourmaline and zircon.—Tourmaline and zircon are generally minor in quantity in first-cycle sediments. Although widely distributed, zircon and tourmaline are not quantitatively important in the heavy mineral suite transported by streams now draining the Front Range petrographic province. The predominance of these two minerals in Dakota sediments suggests concentration over long periods of geologic time.

2. Shape and rounding of tourmaline and zircon.—Most tourmaline grains are elliptical and well-rounded. A few grains are in subhedral to euhedral prisms. The zircons may be divided into two almost equal groups, one anhedral, elliptical, and well-rounded, the other euhedral and exhibiting very little wear. Although some rounding of zircon may take place in igneous rocks, due to resorption, most elliptical, well-rounded zircons (and tourmalines) result from abrasion during transportation. The presence of anhedral and euhedral zircons and tourmalines in the same samples of Dakota sandstones suggests that two generations of these minerals are present.

It is possible that the elimination of the less-resistant minerals and the concentration of the more stable minerals may result from intrastratal solution of the unstable minerals after deposition. In

general, there is an increase in complexity of the heavy mineral suites in the younger Cretaceous sandstones. However, several factors indicate that the supply of first-cycle sedimentary detritus to Hygiene and younger sandstones was of equal importance. These factors are:

1. Preliminary studies of the Jurassic "Dr. Bond" sandstone in the Boulder area indicate that it contains a heavy mineral suite which is more diverse than that of Dakota sandstones (Goldstein, 1948).
2. Fresh plagioclase, microcline, orthoclase, micas, and considerable amounts of detrital quartzite and chert are noted in almost every sample of Hygiene, Fox Hills, and Laramie sandstones. They are not common in Dakota sandstones (except for chert in the basal conglomerate).
3. The interval between the time of deposition of the Dakota and Laramie sandstones is only a single geologic period, but the heavy mineral suites differ considerably.

Aberrant Variations in Mineral Composition

Two samples of Dakota sandstones, D-39 and D-40, have heavy mineral assemblages which differ considerably from those of the remainder of the samples. These two samples contain a relatively fresh heavy mineral assemblage with considerable amounts of hornblende and such moderately stable to unstable minerals as epidote, garnet, actinolite, tremolite, and apatite. Both samples are from the Dakota group at Eldorado Springs; sample D-39 is from the basal conglomerate member, whereas D-40 is from the upper sandstone. A heavy mineral analysis of sample D-41 from the middle sandstone at Eldorado Springs indicates that the distinctive fresh mineral assemblage does not persist vertically through the sediments of the Dakota group at this locality, for sample D-41 has a restricted suite of heavy minerals.

This variation in mineral composition at Eldorado Springs is considered to result from a combination of the following factors:

1. A "sealed environment" in the upper sandstone and basal conglomerate at Eldorado Springs, which tended to preserve the less resistant minerals by protecting them from intrastratal alteration.
2. A monadnock, erosional remnant of the Ancestral Rockies, near Eldorado Springs during Dakota time. This monanock or "Dakota island" furnished fresh detritus to the area.

The concept of a "sealed environment" is discussed by Pettijohn (1941). He considers that the ability of a mineral to survive intrastratal solution depends on the following factors:

1. Nature of the mineral.
2. pH of interstitial solutions.
3. Permeability of the bed.
4. Velocity of flow of ground water.
5. Temperature
6. Geologic age of deposit.

Pettijohn states that, for any particular formation, the unknown conditions (2, 3, 4, 5) may be such as to form a sealed environment in which minerals of low stability may survive longer than more stable species in younger deposits subject to strong water flow.

It seems probable that well-developed silicinate cementation in a sandstone, with almost complete elimination of the permeability of the affected stratum, would be an ideal sealed environment. Silicinate cementation is dominant in samples D-39 and D-40, but is minor in sample D-41. However, complete interlocking of quartz grains by secondary enlargement only occurs at places in slides D-39 and D-40, and silicinate cementation is no more complete than in other sections with typical Dakota heavy mineral assemblages. Some contribution of fresh material is necessary to explain the aberrant mineral assemblages in the Eldorado Springs area. It is considered that this same partially first-cycle assemblage was also deposited in the middle sandstone at Eldorado Springs, but, be-

TABLE 3.—*Heavy mineral composition of samples of Hygiene sandstones*

Mineral Name	Sample Number and Percentages			
	H-1	H-2[1]	H-3[1]	H-5[1]
Ilmenite	9	11	11	14
Leucoxene	25	21	31	27
Tourmaline	4	4	13	4
Zircon	12	33	27	10
Staurolite	P	P		P
Garnet	7	8	6	24
Rutile	3	3	3	3
Titanite	1	P	P	
Hornblende		1	1	P
Chlorite		P	1	
Apatite	3			
Biotite	15	10	3	P
Muscovite	7	6	3	5
Epidote	2	2	1	3
Carbonates	3			
Pyrite	2		P	6
Limonite and Hematite	5			

[1] Sample treated with HCl.

P—present in quantities less than 1 per cent.

TABLE 4.—*Location of samples of Hygiene sandstones used in heavy mineral studies*

Locality No.	Stratigraphic Position	Sample No.
5	Main ridge-forming sandstone	H-5
7	Sandstone 5 feet below main ridge-forming sandstone	H-1
	Main ridge-forming sandstone	H-2
	Sandstone 5 feet above main ridge-forming sandstone	H-3

cause silicinate cementation and a sealed environment were lacking, the more unstable minerals were eliminated by postdepositional intrastratal alteration.

HYGIENE SANDSTONES

Description of Heavy Mineral Suite

The heavy mineral composition of some sandstones from the Hygiene sandstone member of the Pierre formation is shown in table 3. The location of these samples is shown in table 4. A star diagram of the average heavy mineral composition is shown in figure 3. In addition to the minerals in table 3, a few grains of the following minerals were noted:

Galena
Monazite
Kyanite
Piedmontite (?)

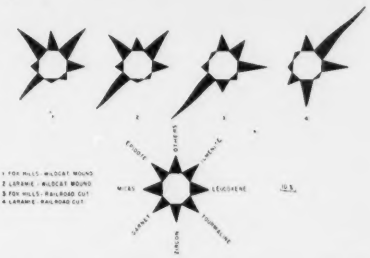


FIG. 4.—Star diagrams of average heavy mineral composition of Fox Hills and Laramie sandstones at Wildcat Mound and the railroad cut north of Leyden Gulch.

FOX HILLS SANDSTONES

Description of Heavy Mineral Suite

The heavy mineral composition of some Fox Hills sandstones is shown in table 5. Location of these samples is shown in table 6. A star diagram of the average heavy mineral composition of Fox Hills sandstones is illustrated in figure 3, and a star diagram of the average composition at two important localities is given in figure 4. In addition, a few grains of the following minerals were identified:

Tremolite
Glauconite (?)
Native Copper (?)
Collophane (?)
Kyanite
Cassiterite (?)
Hypersthene

TABLE 5.—*Heavy mineral composition of samples of Fox Hill sandstones*

Mineral Name	Sample Number and Percentages															
	FH 15[1]	FH 21[1]	FH 22[1]	FH 23[1]	FH 24[1]	FH 24A[1]	FH 25[1]	FH 27[1]	FH 29[1]	FH 41[1]	FH 42[1]	FH 43[1]	FH 43A	FH 46[1]	FH 49[1]	FH 50[1]
Ilmenite	24	27	23	25	20	17	18	22	27	33	11	6	6	6	10	8
Leucoxene	9	10	10	14	7	16	20	10	6	36	43	14	7	20	9	8
Tourmaline	P	2	8	3	4	4	6	5	2	4	4	3	1	2	3	6
Zircon	3	4	P	4	4	2	1	1	3	4	9	9	12	2	4	12
Staurolite	2	3	2	5	8	1	1	4	3	2	P	P	2	P	1	
Garnet	45	21	16	18	19	16	12	28	34	4	22	60	32	64	64	59
Rutile		P	4	P	P	1	2	1	P	P	P	2		P	1	2
Titanite	9	5	9	3	4	5	5	4	7		1	1		P	P	2
Hornblende	P		P		1	P			P	P	P	P				
Chlorite	P	1		P	P	1	1		P		1				1	
Apatite													11			
Biotite	1	3	3	2	5	P	3			5	2	2	3	P	3	
Muscovite	1	4	4	1	6	1	4	P	P	7	1	1	2	P	2	
Epidote-Clinozoisite	5	20	21	23	16	35	25	23	15	P	2	2	P	P	2	2
Monazite					P						P		P			1
Limonite & Hematite													19			
Pyrite			P		P					P	P		2			
Galena	P		P	P					P				1			

[1] Sample treated with HCl.
P—present in quantities less than one per cent.

TABLE 6.—*Location of samples of Fox Hills sandstones used in heavy mineral studies*

Locality No.	Stratigraphic Position	Sample No.
4	Base of massive gray, cross-bedded sandstone (Mather *et al.*[1] No. 30)	FH-21
Wildcat Mound	5 feet above FH-21	FH-22
	5 feet above FH-22	FH-23
	5 feet above FH-23	FH-24 & FH-24 A
	5 feet above FH-24 (Top of Mather *et al.*[1] No. 30)	FH-25
	5 feet above base of Milliken sandstone (Mather *et al.*[1] No. 12)	FH-27
	Top Milliken sandstone	FH-29
8 White Rocks	Near base of Milliken sandstone	FH-15
11	Twenty feet above base of 30-foot sandstone (LeRoy's[2] No. 2)	FH-50
Railroad cut N. of Leyden Gulch	Five feet above FH-50	FH-49
	Fourteen feet above FH-49 (9 feet above base of LeRoy's[2] No. 1)	FH-46
	Fifteen feet above FH-46	FH-43 & FH-43 A
	Five feet above FH-43	FH-42
	Five feet above FH-42 (Top of LeRoy's No. 1)	FH-41

[1] Mather, K. F., *et al.*, *1928 U. S. Geol. Survey Bull.* 796-B, p. 98.
[2] LeRoy, L. W., *1946, Colorado School of Mines Quart.*, vol. 41, no. 2, pp. 89–94.

LARAMIE SANDSTONES

Description of Heavy Mineral Suite

The heavy mineral composition of some Laramie sandstones is given in table 7. Location of these samples is given in table 8. A star diagram of the average mineral composition of Laramie sandstones is shown in figure 3, and a star diagram of the mineral composition at two important localities is shown in figure 4. In addition to the minerals

TABLE 7.—*Heavy mineral composition of samples of Laramie sandstones*

Mineral Name	Sample Number and Percentages									
	D-3	L-16[1]	L-30[1]	L-31[1]	L-32[1]	L-32A[1]	L-33[1]	L-61	L-62[1]	L-63
Ilmenite	28	26	18	21	17	24	18	20	51	59
Leucoxene	24	22	10	9	14	10	13	25	21	7
Tourmaline	7	10	2	2	2	3	2	3	2	P
Zircon	21	10	2	3	3	2	1	12	18	18
Staurolite	P	2	4	3	2	2	6	P	P	2
Garnet	3	22	38	16	34	34	25	21	2	P
Rutile	1	2	P	P	2	1	2	1	P	P
Titanite	P	P	8	4	6	10	7	2	P	3
Hornblende	2	1				P	P	1	P	
Chlorite	2	1	1	2	P					P
Apatite	P						1	P		
Biotite	1	1	1	3	4	1	6	2	1	P
Muscovite	4	2	P	6	1	1	2	2	1	3
Epidote-Clinozoisite	2		15	29	10	11	17	1	1	3
Limonite & Hematite	4							8		P
Galena					2				1	1
Kyanite				P					1	
Monazite	P				P			P		1

[1] Sample treated with HCl.
P—present in quantities less than 1 per cent.

TABLE 8.—*Location of samples of Laramie sandstones used in heavy mineral studies*

Locality No.	Stratigraphic Position	Sample No.
4 Wildcat Mound	Near base of 24-foot massive sandstone (Mather *et al.*[1] No. 1)	L-30
	Five feet above sample L-30	L-31
	Five feet above sample L-31	L-32 & L-32A
	Top of 24-foot massive sandstone	L-33
8 White Rocks	Basal Laramie sandstone, 5 feet up from Fox Hills contact	L-16
10 Coal Creek	Sandstone ten feet up from ridge-forming member	D-3
11 Railroad cut N. of Leyden Gulch	Buff sandstone at Fox Hills contact (LeRoy's[2] No. 44)	L-61
	Ten feet above L-61. Near base of massive sandstone (LeRoy's[2] No. 42)	L-62
	Near top of massive sandstone (LeRoy's[2] No. 42)	L-63

[1] Mather, K. F., *et al.*, *1928*, *U. S. Geol. Survey Bull.* 796-B, p. 98.
[2] LeRoy, L. W., *1946*, *Colorado School Mines Quart.*, vol. 41, no. 2, pp. 89–94.

listed in table 7, a few grains of the following minerals have been identified in Laramie sandstones:

Tremolite
Augite (?)
Zoisite
Sillimanite, var. fibrolite

Fox Hills—Laramie Relationship

The boundary between the Fox Hills and Laramie formations is difficult to distinguish at some places. Lovering *et al.* (1932) state:

The top of the Fox Hills formation shall be

considered as the horizon above which the section is composed predominantly of fresh- and brackish-water deposits accompanied by coals and lignitic shales, and below which it is predominantly marine.

This distinction on the basis of lithology not only transgresses time lines but gives the impression of a continuity of deposition which may be incorrect. Moody (1947 a and b) discusses the complex relationship of the Fox Hills and Laramie formations in the Golden, Colorado, area in two recent articles. He concludes (1947b, p. 1469):

*** the basal Laramie sand rests on different zones of the Montana group at different localities within the area. Locally as much as 800 feet of section is missing between the Laramie and the upper Pierre.

A preliminary study of the heavy mineral assemblages of Fox Hills and Laramie sandstones was made in this study. The composite mineral assemblages of Fox Hills and Laramie sandstones are quite similar (fig. 3). By plotting star diagrams of the mineral composition of these sands at two widely separated localities, some very different facts are revealed (fig. 4). The two localities are (1) Wildcat Mound, and (2) the exposures in the railroad cut near Leyden Gulch north of Golden. There is little resemblance between the percentages of heavy minerals in the Fox Hills at these two localities, and even less between the percentages of heavy minerals in the Laramie sandstone. The star diagrams for the mineralogy of the Fox Hills and Laramie sandstones at Wildcat Mound are remarkably similar. In contrast, the heavy mineral percentages of the Fox Hills and Laramie sandstones at the railroad cut have little resemblance.

The significance of these facts is not entirely clear but the following generalizations seem valid:

1. It is considered that the section at Wildcat Mound indicates continuous deposition of sediment derived from identical terranes throughout Fox Hills-Laramie time. Mineralogically, the Fox Hills and Laramie formations are one and the same at Wildcat Mound.

2. The Fox Hills and Laramie sandstones at the railroad cut contain similar heavy mineral assemblages, but the mineral percentages are quite different. The Fox Hills at this locality is characterized by an ilmenite-leucoxene ratio of 0.5 while the Laramie sandstones have an ilmenite-leucoxene ratio of 2.4. Furthermore, the abundant garnet of Fox Hills time is greatly reduced in the Laramie sediments. It is considered either that (1) a definite depositional break separates the two formations at this locality, or (2) that the parent terranes of the two formations were different. The latter possibility is considered more probable; the flood of ilmenite in the Laramie probably accompanied a local uplift in the early stages of the Laramide revolution.

The need for further study of the Fox Hills-Laramie relationship is obvious. It would seem from these preliminary results that lateral variation in the heavy mineral assemblages of Fox Hills and Laramie sediments is more important than vertical variation.

MINERAL STABILITY

General Comments

Many writers have demonstrated that the complexity of a given suite of heavy minerals decreases with increasing geologic age; i.e., Recent sediments derived from a given igneous or metamorphic terrane contain many mineral species that have been eliminated from older sediments derived from the same terrane. The factors which control mineral stability in sediments have been discussed by Pettijohn (1941), Russell (1937), Goldich (1938), Boswell (1933), Thoulet (1913), Smithson (1941), Dryden and Dryden (1946), and Allen (1948). The results of their studies are incorporated in tables entitled "stability series,"

"order of destruction," "order of persistence," etc. Some of the earlier writers imply that the results obtained are valid under any and all conditions. When one considers the wide range of geologic conditions affecting the preservation or destruction of a given mineral in a sediment, it becomes clear that any single stability series will either be erroneous under certain conditions, or must be so generalized as to be of little value in detailed work.

The present study of heavy minerals from Cretaceous sandstones in the Front Range area furnishes considerable information in regard to mineral stability. In part this study corrobates, in part it modifies, conclusions resulting from observations on other sediments in other areas.

From the time of the rise of the Ancestral Rocky Mountains in late Pennsylvanian time to the Laramide Revolution, there was little volcanic or intrusive activity in the Front Range area of north-central Colorado. The parent terrane of the Pennsylvanian Fountain formation is essentially the parent terrane of the Upper Cretaceous Laramie formation, although the Fountain formation is composed almost entirely of first-cycle sediments, whereas the Laramie contains some reworked material. During the Cretaceous the following conditions are considered to have prevailed in regard to derivation of the sediments:

1. *Dakota group*—derived almost entirely from reworked sediments. Addition of fresh material only in restricted, widely separated areas close to monadnocks above the Cretaceous peneplain ("Dakota islands").

2. *Hygiene sandstones*—derived mostly from reworked sediments. Definite, widespread addition of fresh material probably indicates that the pre-Cambrian complex was exposed in some areas as early as Hygiene time.

3. *Fox Hills and Laramie sandstones*—composed for the most part of fresh, first-cycle sediments. Occasional floods of less-resistant minerals probably mark the time of local uplifts.

In addition to the factor of the source of the sediments, the length of time available for diagenetic alteration of the mineral grains must be considered. The Dakota group is the oldest, including sediments of Lower and Upper Cretaceous age, whereas the Laramie formation is the youngest and near the end of the Cretaceous.

Many mineral species, among them olivine, topaz, and andalusite were not found in any of the sandstones. Other minerals, such as kyanite, sillimanite, the amphiboles, zoisite, monazite, and anatase occur only sporadically in small quantities and are not discussed. Results of observations on the predominant mineral species in the sandstones studied are summarized below.

Stability of Individual Minerals

Garnet.—The stability of detrital garnets in sediments has been discussed by Boswell (1933), Pettijohn (1941), Smithson (1941), and most recently, by Allen (1948), who summarized many previous studies. Some writers consider garnet as unstable (Smithson, 1941; Dryden and Dryden, 1946) whereas others consider garnet very stable (Milner, 1923). Allen (1948, p. 42) states:

> The apparent contrary statements about garnets being very stable and also being very easily altered may be reconciled, if some members of the garnet group are more resistant to chemical weathering than are others. If garnets can be liberated by rapid erosion in advance of their chemical decomposition, they offer strong resistance to abrasion.

The results of the present study indicate that garnets are moderately stable in Cretaceous sediments of the Front Range, and that the disappearance of garnets from a sediment is due to their inability to withstand long-continued chemical attack, either before or after deposition. There are only a few scattered garnets in the sandstones of the Dakota group, whereas there is an abundance of

garnets in the Hygiene, Fox Hills, and Laramie sandstones. All the garnets in the Dakota sandstones and almost all the garnets in the Hygiene sandstones are of the colorless variety, whereas golden and brown garnets are noted in many slides of heavy minerals from Fox Hills and Laramie sandstones.

In addition, etching is noted in many garnets of the Upper Cretaceous sandstones. This alteration is along dodecahedral planes and serves to emphasize the weak parting. Garnets are ubiquitous in the modern Front Range petrographic province, and probably were supplied to sediments derived from this province whenever the pre-Cambrian complex was exposed. The lack of garnets in sediments of the Dakota group apparently results from their elimination in the several cycles of erosion, transportation, and deposition before the sediments of the Dakota group were finally deposited.

Staurolite.—This mineral is generally considered to be unstable in sediments (Smithson, 1941). The frayed edges typical of detrital staurolite are generally attributed to etching along the planes of the prismatic cleavage, considered by Boswell (1933) to result from decomposition or solution. Etched staurolite was also noted in the present study. However, staurolite is a common constituent of the Dakota sandstones, from which all but the most stable mineral species have been eliminated. For this reason it is considered stable in the Front Range petrographic province.

Zircon, Tourmaline, and Rutile.—These three minerals are the most stable in Cretaceous sediments of the Colorado Front Range. Their occurrence is widespread in all the sandstones studied.

Ilmenite and Magnetite.—The relative gross abundance of ilmenite and magnetite in sediments first derived from the Ancestral Rockies may account for their survival and their widespread occurrence in all samples studied, but both are considered to be relatively stable in Cretaceous sediments of the Front Range. Furthermore, it is probable that the ratio of ilmenite to leucoxene, averaged for an entire suite of samples of approximately the same age, to some extent indicates the amount of fresh material contributed to the sediment by the parent terrane.

Sphene and Epidote.—Only a few grains of these minerals were found in Dakota and Hygiene sandstones, whereas they are important constituents of Fox Hills and Laramie sandstones. Thoroughly altered grains of both minerals frequently were noted, but fresh, relatively unaltered grains also occur. Both minerals are considered somewhat stable in Cretaceous sandstones of the Colorado Front Range.

Biotite and Muscovite.—Micas were noted in almost every sample. Occasional floods of micas in siltstones and very fine sandstones more probably reflect the size distribution of the sample and the effects of sorting than the resistance of biotite and muscovite to decomposition.

Front Range stability series.—The following order of stability, from most stable to least stable, appears to prevail in Cretaceous sediments of the Colorado Front Range:

1. Zircon
2. Tourmaline
3. Rutile
4. Staurolite
5. Magnetite
6. Ilmenite
7. Garnet
8. Muscovite
9. Biotite
10. Sphene
11. Epidote

REFERENCES

ALLEN, V. T., *1948* Weathering and heavy minerals: *Jour. Sedimentary Petrology*, vol. 18, no. 1, pp. 38–42.

BOSWELL, P. G. H., *1933. On the mineralogy of the sedimentary rocks:* Thomas Murby & Co., London, 393 pp.

DRYDEN, LINCOLN and DRYDEN, CLARISSA, *1946.* Comparative rates of weathering of some common heavy minerals: *Jour. Sedimentary Petrology*, vol. 16, pp. 91–96.

GOLDICH, S. S., *1938.* A study in rock-weathering: *Jour. Geology*, vol. 46, no. 1, pp. 17–59.

GOLDSTEIN, AUGUST, JR., *1948.* Dakota group of the Colorado Front Range: Unpublished Ph.D. thesis, University of Colorado, 160 pp.

KRYNINE, P. D., *1943.* Diastrophism and the evolution of sedimentary rocks: Mimeographed syllabus of Am. Assoc. Petroleum Geologists distinguished lecture.

———, *1946.* The tourmaline group in sediments: *Jour. Geology*, vol. 54, no. 2, pp. 65–87.

LEROY, L. W., *1946.* Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: *Colorado School of Mines Quart.*, vol. 41, no. 2, 115 pp.

LOVERING, T. S., AURAND, H. A., LAVINGTON, C. S., and WILSON, J. H., *1932.* Fox Hills formation, northeastern Colorado: *Am. Assoc. Petroleum Geologists Bull.*, vol. 16, no. 7.

MATHER, K. F., GILLULY, JAMES, and LUSK, R. G., *1928.* Oil possibilities of northeastern Colorado: *U. S. Geol. Survey Bull.* 796-B, p. 98.

MILNER, H. B., *1923.* The study and correlation of sediments by petrographic methods: *Mining Mag.*, vol. 28, pp. 80–92.

MOODY, J. D., *1947a.* A study of the Laramie formation in the Golden area: *Compass of Sigma Gamma Epsilon*, vol. 24, no. 3, pp. 147–156.

———, *1947b.* Upper Montana group, Golden area, Jefferson County, Colorado: *Am. Assoc. Petroleum Geologists Bull.*, vol. 31, no. 8, pp. 1454–1471.

PETTIJOHN, F. J., *1941.* Persistence of heavy minerals and geologic age: *Jour. Geology*, vol. 49, pp. 610–625.

———, *1949. Sedimantary Rocks:* Harper & Bros., New York, 526 pp.

RUSSELL, R. D., *1937.* Mineral composition of Mississippi River sands: *Geol. Soc. America Bull.*, vol. 48, pp. 1307–1348.

SMITHSON, F., *1941.* The alteration of detrital minerals in the Mesozoic rocks of Yorkshire: *Geol. Mag.*, vol. 78, pp. 97–112.

SWINEFORD, ADA and WILLIAMS, H. L., *1945.* The Cheyenne sandstone and adjacent formations of part of Russell County, Kansas: *Kansas Geol. Survey Bull.* 60, pt. 4, pp. 105–168.

TESTER, A. C., *1931.* The Dakota stage of the type locality: *Iowa Geol. Survey*, vol. 35, pp. 199–332.

THOULET, J., *1913.* Note de lithologie sous-marine: *Ann. Inst. Oceanography*, vol. 5, fasc. 9.

WINCHELL, A. N., *et al., 1936.* Report of the committee on accessory minerals of crystalline rocks: Appendix F, *Ann. Rept. Div. Geology and Geography for 1935–36, Nat. Research Council.*

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 98–106
FIGS. 1–2, JUNE, 1950

TRANSPORTATION OF SEDIMENT BY BUBBLES[1]

HENRY W. MENARD
Harvard University

ABSTRACT

Bubbles adhere to sediment in water and facilitate its transportation both in suspension and as bed-load. The physical limitations on the formation of bubble-grain agglomerates are analysed, and natural environments favorable for their occurrence are discussed. The agglomerates influence the sorting as well as the transportation of sediment.

INTRODUCTION

The transportation of some sediment is facilitated and speeded because bubbles attached to the grains lessen their resistance to movement. The writer observed this phenomenon while experimenting with the transportation of sediment in a flume at the Woods Hole Oceanographic Institution during the summer of 1948. If sand was poured into the flume while it was full of water, many of the grains proved to have bubbles adhering when they came to rest on the bed. The bubbles were not evanescent nor were they easily separated from the grains. Some grains with one or more bubbles attached bounced along the bottom as if they were free balloons with an excess of ballast. Such particles collected on the lee sides of ripples, and remained there while the ripples slowly migrated downstream. At the time they were considered to be a nuisance because they moved so readily that they obscured the initial movement of the other grains—which was the subject of the investigation. Consequently they were swept away by concentrating and accelerating the current where they were clustered, and no special study was attempted. Figure 1, which shows a 2 mm grain with adhering bubbles, is based on a sketch made while observing the bed of the flume through a glass panel in the side. This grain moved readily although the water velocity was not competent to disturb smaller sand grains.

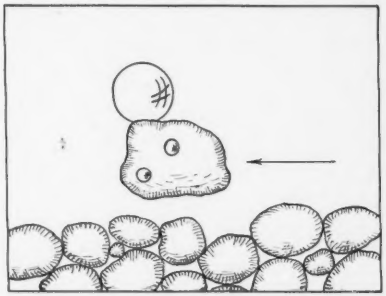


FIG. 1.—A 2 mm quartz grain buoyed by one large and two small bubbles. Arrow indicates direction of flow.

The writer knows of no published observations of bubbles attached to grains in the bed-load of natural watercourses, probably because the bubbles are destroyed when a sample of the bed is brought to the surface. However, Nordenskiold (1900) noted bubbles on the underside of floating stones, and the flotation of boulders of peaty alluvial soil has been ascribed in part to entrapped air (Happ, 1943).

Bubbles anchored to the bottom by the weight of attached mud were observed by Twenhofel (1921) who also found trails in soft mud caused by the stranding of floating bubbles, but he does

[1] Contribution No. 476 from The Woods Hole Oceanographic Institution.

not report any movement of bed-load in this manner. One must turn to the related field of ore flotation to find reference to bubbles affecting the motion of sediment both in suspension and in the bed-load. Gaudin (1939) distinguishes three types of ore flotation of which two are pertinent: "In *froth flotation* or flotation proper, adhesion is effected between gas bubbles and small particles in such a way that the specific gravity of the mineral-air associations is less than that of the pulp so that they rise in that pulp. * * * In *agglomeration*, loosely bonded associations of particles and bubbles are formed which are heavier than water but lighter and coarser than the particles adhering to water***." Thus there exists a whole technology based on the type of bubble transportation described in this paper. In accordance with the common usage in mineral dressing, sediment grains with attached bubbles hereafter will be called *agglomerates*.

PHYSICAL LIMITATIONS

Bubbles which are in contact with sand grains will remain so if the forces which tend to hold them together exceed those which pull them apart. The attraction of the sub-surface molecules in a liquid upon the surface molecules results in the so called "surface tension" which has a value of 72 dynes per centimeter for water at 20°C. The force due to surface tension acting at a bubble-grain-water interface is shown in figure 2 (after Gaudin, 1939). In this instance the bubble is much larger than the grain of sediment. The vertical component of the force is equal to

$$(2\pi r \sin \omega) T \sin (\theta - \omega)$$

in which r is the radius of the grain, T is the surface tension, θ is the angle between the grain and the bubble at the contact, and ω is one half the apical angle subtended by the circle of contact.

The forces which tend to separate the bubble and grain differ, depending on whether the agglomerate is at the surface of the water, on the bed, or in motion in the water. A large bubble attached to a small grain rises to the water surface, but it may or may not penetrate it. If not, the bubble may be considered as stationary, and the force tending to pull the grain away is equal to the weight of the grain in water. At the other extreme

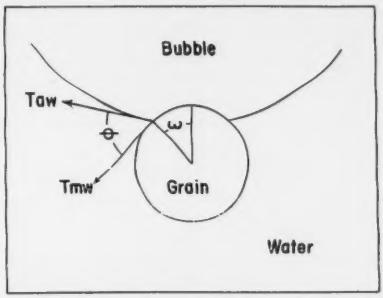


FIG. 2.—The forces due to surface tension acting at a bubble-water-grain interface. Taw is the force at the bubble-water surface, and Tmw the force at the grain-water surface, θ is the angle between the two, and ω is one half the apical angle subtended by the three phase contact.

the agglomerate rests on the bed because the buoyancy of the bubble is less than the weight of the grain in water. The grain is stationary in this case, and the force tending to pull the agglomerate apart is equal to the buoyancy of the bubble. If the weight of the grain and the buoyancy of the bubble are approximately equal, the agglomerate moves whenever the water does. In the turbulent flow characteristic of natural watercourses (Hjulström, 1935), this type of agglomerate usually is part of the suspended load which is not in contact with either the bed or the water surface. The important forces tending to pull the bubble and grain apart result from the sudden accelerations caused by eddies. The tenacity of the agglomerate is highly dependent on the contact angle between the grain and the bubble, which in turn depends on the adherence between water

and the grain. The contact angle will be discussed in the succeeding paragraphs, but for the present it may suffice to say that galena discs (diameter is the same size as the thickness) will not separate from bubbles although the acceleration is one hundred times gravity, as long as the contact angle is 0° 7′ 30″ for grains of 0.01 mm diamter, or 3° 8′ for grains of 0.05 mm diameter (Gaudin, 1939). Since the accelerations due to turbulent eddies are comparatively small, quartz grains which are even slightly resistant to wetting probably cannot be separated from bubbles when the agglomerate is in suspension.

The all-important contact angle (θ in fig. 2) is a measure of the wettability or adherence between water and a grain. If it is measured through the water in a section normal to the three phase contact, the contact angle of a wholly wettable substance is zero, that is the water is capable of spreading over an infinite surface of the material. Many minerals have a zero contact angle if they are uncontaminated. On the other hand, organic materials such as oils and waxes have a large contact angle because they adhere to air rather than to water. The wettability of the common detrital minerals has been the subject of much research, but the results at present are equivocal because some investigations indicate that sand grains will adhere to air, and others do not. Gaudin (1939) states that most inorganic minerals adhere to water, and he believes that the minerals which appear to adhere to air do so for the reason that the surface has been contaminated by minute quantities of organic matter. McKelvey (1941) demonstrates that quartz grains can be protected from wetting by a surface layer of adsorbed air instead of organic matter, and that the air layer is not displaced readily by water because sand can float for more than four months. Be this as it may, the transportation of either suspended sediment or bed-load by bubbles requires merely that grains adhere to air, and this is commonly observed. If the writer's experience may be generalized, more grains of natural sand will adhere to bubbles than will not.

The effect of particle shape and density upon the tenacity of a grain and a bubble is exactly the same as if the grain were floating and the bubble were the water surface. McKelvey's analysis (1941) of the flotation of sand indicates that the more irregular the shape and the smaller the density of a grain. the greater is the tenacity of a bubble-grain agglomerate.

The depth of the water, and the pressure which results from it, do not affect flotation at the surface, but they influence the buoyancy and ease of transportation of a grain with adhering bubbles because the volume of the bubbles decreases with depth. Nevertheless, a depth of 10.3 meters is necessary to halve the size of a bubble compared to its volume at the surface, so the effect of depth in most rivers is not very significant. Even qualitatively, the depth does not determine whether an agglomerate sinks or floats. If one formed at the surface is so dense that it starts to sink, it continues to sink because it becomes denser as the depth increases. The reverse is true of a rising agglomerate.

NATURAL OCCURRENCE

The transportation of sediment by bubbles requires that the two be brought together to form an agglomerate. This may occur at the water surface, within the water, or on the bottom. At the surface, bubbles may become attached to grains when sand falls into water due to the carving of stream banks, or when it is blown in by the wind. Rapidly moving water may entrain air, and turbulent mixing brings suspended grains and bubbles in contact. On the bottom, bubbles are commonly formed in sediment due to the generation of gas by decaying organic matter, and also for the reason that air which is trapped in sand by encroaching waves breaks through the bottom in the form of bubbles. The influence of these various means of forming

bubbles in sediment-laden water will be the subject of the succeeding paragraphs.

Caving of River Banks

Many modern rivers and streams are entrenched in alluvial floodplains, so that it is commonplace to see sediment cave into rivers as the banks are undercut due to meandering or rising flood waters. In the flume tests at Woods Hole, the procedure of pouring sand into the water is analogous to introducing it by caving undercut banks, because in each case the grains enter the water by a free fall in air. It may be assumed, therefore, that the bubble-grain agglomerates observed in the flume also occur in natural watercourses due to the circumstance described. The writer made a few simple experiments in order to determine the effect of the distance of fall upon the abundance of the resultant agglomerates. A dry sand with a median size of 0.7 mm, a sorting coefficient of 2.0, and a range in size from about 0.1 to 4.0 mm was dropped from different heights into a beaker full to a depth of 10 cm with freshly drawn tap water. About a gram of sand was used in each test. A few small bubbles became attached to grains when the sand was dropped from a height of only 2 cm above the water surface. A drop of 10 cm produced more agglomerates with larger bubbles, and a fall of 30 cm yielded many agglomerates including some with bubbles more than 1 mm in diameter. Two mm bubbles adhered to grains when the sand was dropped 1 meter, and these were abundant in the instance of a 2 meter fall. In general, the agglomerates on the bottom became more numerous, and the size of the bubbles increased with an increase in the free fall. Two tests with boiled, air-free water yielded the same results.

It is often stated that wholly wet sand grains will not float; if not, they should not form agglomerates. To test this statement, two samples of sand which, when dry, formed agglomerates were also dropped into water when wet. Repeated tests yielded a total of only two agglomerates, and the possibility existed that such a small number might be caused by adulterant organic matter in the sand. For this reason, the adhesion of air to wet sand was also tested by boiling water with sand in it, and by blowing bubbles through sand immersed in water. Agglomerates were produced in profusion in each instance, and it is apparent that bubbles adhere to grains in water. These latter experiments will be described in some detail in a later part of this paper.

The influence of sorting and median size was measured by testing a monodisperse sand with a median diameter of 0.35 mm. When this sand fell into the water from a height of 1 meter, so many agglomerates developed that the bottom of the beaker resembled a froth, but none of the bubbles were more than about 1 mm in diameter. Large grains apparently tend to produce large bubbles, and small grains entrain only enough air to form small ones.

Behre (1926) made similar tests relating the height of free fall to the percentage of grains which would float on the water surface. He found that over 9 percent of a monodisperse sand with a median size of 0.25 mm would float if dropped from a height of 5 cm, but a fall of 20 cm caused all but about 3 percent of the grains to sink. Part of the sand floated on the water surface in the present tests. Grains as large as 2 mm floated when sand was dropped from a height of 2 cm, but at greater heights only much finer sediment floated. The percentage of floating sand did not diminish whether the sample fell 30 or 200 cm, probably because the grains smaller than about 0.1 mm do not attain a settling velocity adequate to penetrate the water surface. This conclusion is confirmed by the following analysis. By Stokes' law, the terminal settling velocity of a spherical grain which falls without creating turbulence is

$$V = \frac{2gr^2(\sigma_G - \sigma_F)}{9\mu}$$

$$V = 74.5 \text{ cm/sec}$$

r = radius in cm = 0.005
σ_G = density of grain in gm/cm³ = 2.6
σ_F = density of fluid = negligible (for air)
μ = viscosity of fluid in dyne sec/cm² = $1.9 \cdot 10^4$ at 20°C.

Nevin's precise determinations of the settling velocities of grains in water (1946) show that Stokes' law applies to grains with a Reynolds number less than about 20 to 30. In the present instance

$$R = \frac{Vd}{\nu}$$

$$R = 4.4$$

R = Reynolds number
V = velocity in cm/sec
d = diameter in cm
ν = kinematic viscosity in cm/sec.

Therefore 74.5 cm/sec is the maximum velocity of a 0.1 mm grain in still air. If it is assumed that the maximum possible vertical distortion of the water surface is equal to the radius of the grain (if the grain is not to penetrate the surface and sink), the negative acceleration of the grain upon striking the surface is

$$a = \frac{V^2}{2s}$$

$$a = 5.6 \cdot 10^4 \text{ cm/sec}$$

s = vertical distance the surface is distorted downward.

The mass of the grain is $1.36 \cdot 10^{-6}$ gram, so the force of the falling grain on the surface is

$$F = ma + mg$$

$$F = 0.077 \text{ dynes.}$$

The acceleration a, and therefore the force F, diminishes if the water surface is capable of distorting more than a distance equal to the radius of the grain. The force exerted by the surface tension tends to hold the grain at the surface. If it exceeds 0.077 dyne, the grain floats. As indicated in the section on Physical Limitations, this force is equal to

$$(2\pi r \sin \omega) T \sin (\theta - \omega)$$

and since T is 72 dynes per cm, and $2\pi r$ is 0.031 cm, the grain will float if

$$\sin \omega \sin (\theta - \omega) \geqq 0.03.$$

Surface tension, therefore, is capable of separating silt and fine sand from the coarser materials if sediment enters water by a free fall, because the fine grains do not pierce the surface and the coarse ones do. As has been mentioned, many of the particles smaller than 0.1 mm float if a sand with a sorting coefficient of 2.0 is dropped from a height of 1 meter; but when this test is repeated with a monodisperse sand with a median size of 0.35 mm only one or two grains remain on the water surface. The critical size in these tests is in the vicinity of 0.1–0.3 mm; however, turbulence in the air might cause smaller grains to sink, and larger ones to float depending on the motion of eddies.

Blown Sand

The foregoing discussion of the formation of agglomerates by the caving of stream banks applies equally well to sand dropped on water by the wind. Behre (1926) observed sizeable quantities of sand floating on the Ohio River, and he believed that the sand had been blown onto the water. If so, the larger grains pierced the surface and many probably formed agglomerates. Sand dunes on floodplains attest to the frequency with which sand is blown about in the neighborhood of rivers; dustfalls on the decks of ships are not unusual, so wind action also may form agglomerates by dropping sediment far out from the shores of lakes and seas. Most of the material transported for any considerable distance is of the size of clay or silt, and much of it

would be expected to float on the water surface according to the analysis in the preceding paragraphs. However, that analysis concerned still air such as would be encountered by grains falling from river banks. Wind which carries sand is highly turbulent so the velocity at which any grain hits the water is equal to the vector sum of the terminal settling velocity and the instantaneous wind velocity. Since this sum is often larger than the settling velocity alone, some smaller grains may be expected to break the surface and form agglomerates.

Both bubble agglomerates and surface flotation transport sediment which has been dropped on the water surface by the wind or by the caving of stream banks, but, lacking quantitative data, it is impossible to say which is the more important. The question is not entirely academic for Behre (1926) indicates that under some circumstances on the Ohio River, surface flotation by itself is capable of moving 130 tons of sediment per hour while the bed-load movement is only six tons per hour. Certain characteristics of flotation and bubble transportation suggest that the latter process probably moves more sediment. Almost all grains with a diameter of more than about 0.1 mm will pierce the water surface if they fall only a few tens of centimeters. They may or may not form agglomerates with bubbles, but they definitely will not float. Moreover, observations in a hydraulic flume show that the agglomerates are quite durable. Surface flotation, on the other hand, results from a comparatively precarious balance, and floating sand sinks if the water surface becomes rough due to increased turbulence or a gust of wind or a fall of rain. The writer covered the water in a beaker with a layer of floating sand, and then put it under an artificial rain falling from a height of about 50 centimeters. Not only did the floating sand sink, but a large number of agglomerates formed. Thus the very processes which destroy surface flotation may also increase the amount of sediment moved by bubbles.

Entrained Air

Agglomerates form if air, entrained in water, encounters sediment in suspension or on the bottom. This occurs when air is artificially entrained for the purpose of separating minerals by flotation, and it may be assumed that it takes place in nature as well if turbulent water contains bubbles and sediment. However, the frequency may be questioned. The writer tried to produce agglomerates by shaking water and sand together. The sand was immersed in water for some time to insure its being wet, and all agglomerates which formed upon introducing the sand to the water were carefully removed by decantation. The wet, bubbleless sand and water were then shaken vigorously for about a minute. Six tests produced a total of only twelve visible agglomerates.

Lane (1939) found that air is entrained when water flows over the crest of a dam, although a spillway is so smooth that the water may fall 145 feet before it becomes white with entrained air. No air is entrained until the water reaches a critical velocity and turbulence, and the water surface becomes very irregular. In nature, however, air is entrained by water which falls only short distances, and attains comparatively small velocities. The bed roughness of waterfalls usually suffices to produce entrainment almost at the crest. Even in rapids, in which the water flows rapidly but does not fall, rock projections from the sides and bottom of the channel create excessive turbulence and entrain so much air that "whitewater" and "rapids" are synonymous. The bubbles entrained by waterfalls are carried down into potholes and plunge-pools where conditions are favorable for the formation of agglomerates because of the large quantity of sediment in suspension in the water, and because of the violence of the agitation. The heavier agglomerates settle to the bottom and join the bed-load, but the strong eddies probably keep most of the agglomerates

in suspension for some distance downstream from the falls. Material of sand size, after forming agglomerates, is moved very rapidly by a current, and continues to move even if the current becomes so slow that the other grains, which are not in agglomerates, are deposited. A similar rapid and facile transportation of sand should occur within rapids and downstream in more tranquil waters. The white crests of waves also contain entrained air, and the boiling turbulence of surf presents another environment which is favorable for the formation of agglomerates.

Air Trapped or Generated on the Bed

Air bubbles may be formed on the bottom under certain circumstances. Cornish (1921) observed that flooded sands "spouted" air in the form of bubbles, and Twenhofel (1921) stated that in his experiments "when dry earth is flooded, air is expelled in large quantities." More recently, Emery (1945) found that air holes caused by the emission of bubbles are very common on marine beaches. Waves surge up the beach so rapidly that the air in the sand is overrun and trapped, and the air bubbles up into the sand with such vigor that holes are formed in the bottom.

The present writer's experiments demonstrate that bubbles which are produced within the sediment on the bottom are very likely to form agglomerates. Several grams of wet monodisperse sand with a median size of 0.35 mm were placed in a one liter beaker full of water. The sand was stirred and water was decanted until no agglomerates were visible. The beaker was then heated over a low fire until bubbles began to form in and on the sand. Hardly one failed to adhere to some sand grains, so the beaker was soon filled with rising agglomerates and falling sand (resulting from the destruction of bubbles at the surface). In another test, bubbles were formed in the same sand in cold water by blowing into a straw. Once again the bubbles produced agglomerates in profusion. It may be concluded that the transportation of sand in the form of bubble-grain agglomerates is a commonplace occurrence at the strandline, and may also happen whenever flood waters rush over dry sediment.

Decomposition of organic matter underwater produces gas in the form of bubbles, and the bubbles can transport sediment. This mode of transportation occurs so frequently in the treatment of sewage that special provisions must be taken to prevent it. Keefer (1940) says: "Sludge should be removed from the sedimentation tanks as soon as possible. Otherwise decomposition begins with the formation of odorous gases. They buoy up settled solids, which either produce scum or pass off with the effluent." Bubble-grain agglomerates should form in this fashion in swamps, marshes, and wherever else stagnant water may be found. In such environments, currents may be expected to be so gentle that no sediment is transported unless it is supported by bubbles; however, Kershaw (1915) observed that rising bubbles produce eddies which succeed in keeping fine material in suspension in sewage-treatment works. Stagnant water presents the ideal environment for the decomposition of organic material with accompanying formation of agglomerates, but the process may take place elsewhere. Maxson (1940) found gas pits in the sand bars of the Colorado River in the Grand Canyon, and also around Lake Mead, and Griffin (1943) observed vesicles in mud on the floodplains of southwestern Ohio streams. The vesicles were produced in stiff mud by the decomposition of sewage. In the early stages of the decomposition when the mud was fluid, any gas generated must have escaped from the mud into the overlying water, and thus formed agglomerates. Nevertheless any significant transportation of sediment due to the formation of agglomerates by this method must occur in stagnant water. There it may dominate all other modes

of moving sediment because the currents present are seldom strong enough to move silt and sand which are not buoyed by bubbles.

Cavitation

If running water attains a velocity of 14.3 meters per sec. at sea level, bubbles form by cavitation (Hjulström, 1935), and it is possible that they may join sediment and form agglomerates. Cavitation is rare in nature, however, and at cavitation velocities sediment moves very rapidly whether or not it is attached to bubbles. Moreover, bubbles produced by cavitation are destroyed as soon as the velocity decreases. High speed photography reveals that these bubbles may have an existence of only 1/200 of a second (Anonymous, 1949). For these reasons, it seems unlikely that the formation of bubbles by cavitation effects the transportation of sediment.

CONCLUSION

Sediment is tranported in water in agglomerates composed of bubbles and grains held together by surface tension. This mode of transportation is of sufficient importance so that one technology, sewage disposal, takes special precautions to prevent it; and another technology, mineral dressing, uses it to separate ore from gangue by flotation. The bubble-grain agglomerates may be part of the bed-load or they may be suspended or floating just below the surface depending on whether the weight of the grain exceeds the buoyancy of the bubble. The agglomerates are of interest to geologists because they influence the transportation and sorting of sediments, and also for the less important reason that they produce tracks in mud.

Twenhofel (1921) observed that when floating bubbles become stranded in very soft mud they scrape grooves which bear a strong resemblance to worm trails. He states (Twenhofel, 1939) that such grooves can be formed only in very shallow water, and this cannot be questioned in the instance of bubbles floating at the water surface. However, the present study indicates that agglomerates are capable of dragging along the bottom in water many meters deep. Any grooves in mud in deeper water have a much better chance of being preserved in the geological column than they would if formed at the shifting strand line. Some agglomerate grooves would have a variety of shapes in cross section because they would not be cut by the spherical supporting bubble, but by the more or less irregular shape of the suspended sand grain. Agglomerates on the bed of a hydraulic flume saltate or bounce along in a manner which suggests that they are not incapable of simulating irregular tracks as well as worm grooves in mud.

Water tends to sort the sediment which it transports, so that grains of the same size are grouped together when they are deposited; yet a group of minor agents of transportation which depend on the buoyancy of water have the reverse effect, and deposit sediment with little regard for the size. Among these agents are aquatic animals and plants, ice rafting, direct flotation, and bubbles. Agglomerates are transported by water so they should be sorted according to size and density just like all other debris. However, the material which appears in a bottom sample or in a rock is comprised of sediment not agglomerates. Two agglomerates may have the same size and density, and therefore be deposited together, but one may include many small sand grains although the other has but one large one. This reasoning applies also to grains with different shapes and densities. The tendency toward poor sorting exists only when bubbles transport sediment from one environment to another.

Behre (1926) shows that the importance of flotation in the transportation of sediment lies not in the amount of the material but in the speed at which it moves, and that on the Ohio River surface flotation may surpass bed-load movement by twenty times. Sediment

in agglomerates, whether in suspension or in the bed-load, also moves much faster than material which is not buoyed by bubbles; moreover, agglomerates are transported when the current velocity is too slow to produce any general movement of the bed-load. Bubble transportation is not significant when rivers are in flood because so much sediment is moved by other means, but it may be important at low water when the bed is in approximate equilibrium with the energy of the stream. Although quantitative data are lacking, it seems likely that in some circumstances more material is moved by bubbles than by flotation on the water surface, because agglomerates are very durable, whereas rain or rough water breaks up the surface and sinks the floating grains.

It is hoped that this study will direct the attention of field observers to the problem of the transportation of sediment by bubbles, for its importance is suggested both by analysis and by experimentation.

ACKNOWLEDGEMENTS

Mr. Henry Stetson and Drs. R. S. Dietz, K. O. Emery, and R. Dana Russell have read and criticised this manuscript, and it is a pleasure to acknowledge their assistance. The author is also indebted to the Woods Hole Oceanographic Institution for a Summer Fellowship which led to this study.

REFERENCES

Anonymous, *1949*. Life and death of a bubble: *Engineering and Science*, vol. 12, no. 5, pp. 14–16.

Behre, C. H., *1926*. Sand flotation in nature: *Science*, new ser., vol. 63, pp. 405–406.

Cornish, V., *1912*. *Waves of the sea and other water-waves:* T. Fisher Unwin, London, 374 pp.

Emery, K. O., *1945*. Entrapment of air in beach sand: *Jour. Sedimentary Petrology*, vol. 15, pp. 39–49.

Gaudin, A. M., *1939*. *Principles of mineral dressing:* McGraw-Hill, New York, 554 pp.

Griffin, R. H., and Shanklin, R. E., *1943*. Recent deposits of vesiculated mud along southwestern Ohio streams: *Jour. Geology*, vol. 51, pp. 488–495.

Happ, S. C., *1943*. Flotation of peaty alluvial soils: *Am. Jour. Sci.*, vol. 241, pp. 629–639.

Hjulström, F., *1935*. Studies of the morphological activity of rivers as illustrated by the River Fyris: *Geol. Inst. Univ. Upsala Bull.*, vol. 25, pp. 221–528.

Keefer, C. E., *1940*. *Sewage-treatment works:* McGraw-Hill, New York, 673 pp.

Kershaw, G. B., *1915*. *Sewage purification and disposal:* Cambridge Univ. Press, 340 pp.

Lane, E. C., *1939*. Entrainment of air in swiftly flowing water: *Civil Engineering*, vol. 9, pp. 89–91.

Maxson, J. H., *1940*. Gas pits in non-marine sediments: *Jour. Sedimentary Petrology*, vol. 10, pp. 142–145.

McKelvey, V. E., *1941*. The flotation of sand in nature: *Am. Jour. Sci.*, vol. 239, pp. 594–607.

Nevin, C., *1946*. Competency of moving water to transport debris: *Geol. Soc. America Bull.*, vol. 57, pp. 651–674.

Nordenskiold, E., *1900*. Floating stones: *Nature*, vol. 61, p. 278.

Twenhofel, W. H., *1921*. Impressions made by bubbles, rain drops, and other agencies: *Geol. Soc. America Bull.*, vol. 32, pp. 359–371.

———, *1939*. *Principles of sedimentation:* McGraw-Hill, New York, 610 pp.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 107–110
FIGS. 1–2, JUNE, 1950

A SONIC DEVICE FOR UNDERWATER SEDIMENT SURVEYS

E. C. LAFOND, ROBERT S. DIETZ, AND J. A. KNAUSS
U. S. Navy Electronics Laboratory, Oceanographic Studies Section, San Diego 52, California

ABSTRACT

A sonic device for roughly determining sea floor composition is described. It consists of a hydrophone encased in a watertight metal container designed to be dragged along the ocean bottom, and a suitable audio amplifier monitoring equipment located aboard a towing vessel. The frictional noises produced when the metal case is scraped along the bottom are picked up by the hydrophone and fed through cable to the amplifier. Since the noises caused by mud, sand, stony, and rock bottoms differ in character, it is possible to identify the bottom type by listening to the amplifier output. The device is especially useful for making a very detailed survey of a small area in shoal water for the purpose of constructing a sediment distribution chart.

It is sometimes desirable to establish the character of the sea floor in a limited area in sufficient detail to permit the construction of an accurate sediment chart showing the distribution of mud, sand, stony, and rock bottom. For example, a detailed bottom sediment chart is occasionally required for geological information or in connection with marine ecological studies such as those relating to the distribution of fish. Also, detailed sediment information is sometimes required in connection with the installation of equipment on the bottom or with the construction of marine engineering structures. To meet such requirements, a new sonic "sampler," which has been nicknamed the "soundfish," has been developed and successfully tested by the writers. The device utilizes the sound emitted by a metal cylinder dragged along the bottom to determine the continuous character of the sea floor along the course of the ship.

The soundfish as presently developed and used consists of a Brush C-23 hydrophone encased in a watertight metal cylinder which is 22 inches long, four inches in diameter, and weighs 25 pounds (fig. 1). The metal case serves as a sound source as it scrapes along the bottom and also furnishes protection for the hydrophone. Circular ridges are used on the outside of the case to increase the frictional sound developed. The metal case does not necessarily have to be watertight, but this type of construction increases the depth to which the device may be used since the hydrophone will only safely withstand a pressure equivalent to about 60 fathoms. However, the difficulty of the dragging operation and other considerations probably limit the usefulness of this device to continental shelf areas where depths are generally less than 100 fathoms.

The sound emitted by the metal case as it is dragged along the bottom is picked up by the encased hydrophone and transmitted up an electric conductor cable to the ship, where it is monitored with suitable listening equipment. For this purpose, a battery-operated audio amplifier proved satisfactory. If the conductor cable is of a high-tensile-strength type, it may be used for towing. If it is of the usual low-breaking-strength type, it must be lowered along with a steel cable which serves to withstand the stress of towing.

The type of sound emitted by the soundfish is specific for rock, gravel, sand, and mud bottom. Under good conditions a trained observer can even differentiate with some success between fine, medium, and coarse sand. Rock makes continuous loud bongs or clangs, sand makes a heavy scraping or rasping noise, and mud makes a quiet swishing noise. In a mixture of

FIG. 1.—Photo showing the "soundfish." Note also the winch containing wire rope and the smaller reel of conductor cable both of which are used to lower the device to the sea bottom. Official U. S. Navy photo.

coarse and fine material, the noise made by the coarse fraction dominates. It is not possible to describe accurately the noises, and they vary with the sensitivity of the audio amplifier, the speed of the ship, and the resonance of the metal case, so that it is necessary for the observer to train his ear by listening while the equipment is dragged at constant speed over known types of bottom, as determined by grab sampling.

An especially useful function of the soundfish is to establish the boundaries between areas of different types of sediment. Such boundaries cannot be accurately located by spot-sampling methods. Also positive identification of rock bottom is difficult to obtain by grab sampling methods, as the snapper usually comes up empty.

A bottom sediment survey made with the soundfish gives best results when it is supported and checked by occasional bottom sampling. Also, it is useful to correlate the survey with detailed profiles made with a recording echo sounder, as the type of bottom sediment is usually closely correlated with topography. For example, rock bottom is almost invariably irregular whereas sand and mud bottoms are smooth.

A simpler variation of this method of using the noise of an object dragged along the bottom to determine sediment type has been fairly successful. This technique consists of dragging a resonant metal object such as a hollow metal pipe along the bottom with a small diameter wire rope. Some of the noise made by such an object is transmitted up the wire to the boat, where it may be picked up by a contact microphone which is connected to a suitable audio amplifier. The sounds produced by various types of bottom are similar to those detected by the "soundfish" sampler. With this technique, however, the sound signals are weak and it is difficult to eliminate extraneous noises.

In order to give the soundfish a thor-

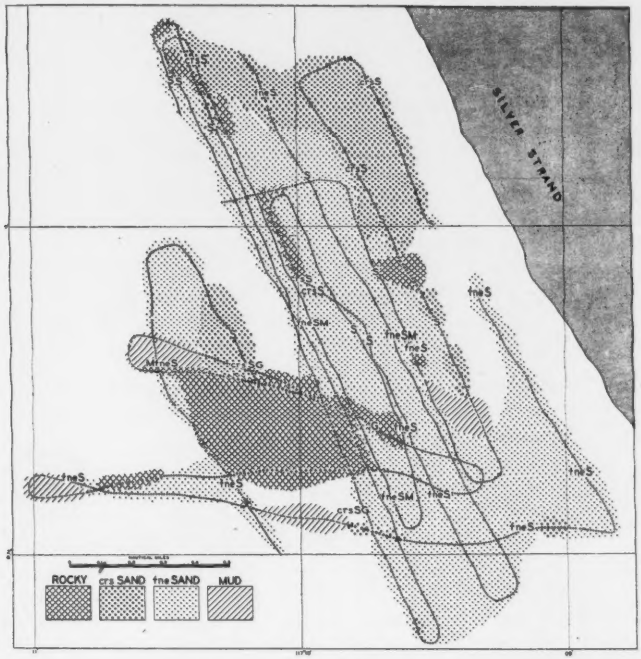


FIG. 2.—Bottom sediment chart of an area off the Silver Strand Beach at San Diego, California, made with data obtained by the "soundfish." The lines on the chart represent the track of the observing vessel. Each "soundfish" observation along the track is represented by a symbol as follows: a cross equals rock or gravel; an open circle equals coarse sand; a dot equals medium or fine sand; and a dash equals mud. The sediment chart is constructed on the basis of these observations. Letter symbols such as fSM (fine sand with mud), etc. indicate identifications made on the basis of bottom samples.

ough field test, a detailed bottom sediment survey was made recently in water of about ten fathoms depth off the Silver Strand beach near San Diego, California, from the research schooner E. W. SCRIPPS of the Scripps Institution of Oceanography. The soundfish was dragged with a five thirty-secondths inch wire rope back and forth over an area of about three square miles which was known to have a variety of bottom types. A conductor cable, through which the sound from the hydrophone was transmitted to the ship, was taped at approximately 20-foot intervals to the steel cable with sufficient slack so that the steel cable alone accumulated the stresses. Fixes were obtained about every two minutes by triangulation, using a sextant aboard ship and measuring the horizontal angles to suitable shore points of known position. The vessel was operated at a speed of from two to four knots, so that the soundfish moved by saltation along the bottom. An observer monitored the audio amplifier and attempted to differentiate between mud, fine sand, medium sand, coarse sand, pebbles, cobbles and rock. Another observer obtained bottom samples at intervals with an underway sampler (Emery and Champion, 1948). It was found that good agreement

was obtained between the actual bottom samples and the bottom character interpreted by the observer listening to the soundfish. Also, the boundaries between different types of bottom could be located with considerable accuracy. With the data obtained from this survey, a sediment chart was constructed showing the distribution of mud, fine and medium sand, coarse sand, and rocky or stoney bottom (fig. 2). It was not practical to attempt to make finer discriminations, such as differentiating between fine and medium sand.

In conclusion, the writers believe that the soundfish is a useful tool for rapidly determining the detailed distribution of bottom sediment types on the continental shelf. The main disadvantage of the soundfish is that somewhat more elaborate equipment is required than is generally readily available to the average worker. The less satisfactory method of dragging a piece of metal on the bottom and listening to the wire with a contact microphone and an audio amplifier is a useful alternative.

REFERENCE

EMERY, K. O., and CHAMPION, A. R., *1948*. Underway bottom sampler: *Jour. Sedimentary Petrology*, vol. 18, no. 1, pp. 30–33.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 111–115
FIGS. 1–2, JUNE, 1950

CONTORTED PLEISTOCENE STRATA AT NEWPORT BEACH, CALIFORNIA

K. O. EMERY
University of Southern California

ABSTRACT

An example of interformational folding in Pleistocene strata of southern California is ascribed to the sinking of a layer of beach sand into an underlying marsh deposit of sandy silt. The sinking is believed to have resulted from a higher bulk density of the sand than of the sandy silt. No lateral sliding was required.

INTRODUCTION

One of the best exposed and easiest accessible examples of interformational folding in southern California occurs in the low cliffs that face the open sea at Newport Beach. The cliffs were originally formed by marine erosion but they were trimmed back slightly during construction of the Coast Highway from Los Angeles to San Diego. As the route is well-travelled, probably hundreds of geologists have noted the folds.

DESCRIPTION

The folds occupy a zone 7 to 9 feet thick near the base of the practically horizontal Pleistocene Palos Verdes sands, which rest upon tilted and bevelled shale probably of Pliocene age. As shown by figure 1, the lowest bed that exhibits any contortion is a gray silty sand (1) which is separated by a thin band of iron stain from a sandy silt (2) of similar appearance. The maximum thickness of both beds exposed above talus is 50 inches. Overlying the sandy silt is a white silty medium sand (3) mostly 8 to 12 inches thick. Next is a 1- to 4-inch bed of compact brown sandy silt (4) followed by a yellow-gray sandy silt (5–6) mostly between 8 and 12 inches thick. The topmost bed involved in the folding is a clean gray laminated medium sand (7) ranging up to 50 inches thick. Above the folded zone the same sand grades upward into coarser laminated sand (8 and 9) containing many large concretions and some very fossiliferous layers. There is no contortion of these upper sands.

The contortion is best developed in a section 180 feet long, in which there are 14 separate and distinct folds. Figure 1 and the photographs of figure 2 show that the sand (7) is deformed into lense-shaped masses, the edges of which are separated by intrusions of the underlying sandy silt (5–6) and in some instances by all of the lower beds, except the lowest sandy silt (1). The latter, however, is slightly bowed upward toward the gap between some of the sand lenses. The top sandy silt continues upward between some of the lenses and then spreads out laterally, almost pinching off sections of the overlying sand. Examination of figure 1 shows that the columns of silt between the sand lenses have no preferred direction of slope and many are nearly vertical. No indication, whatever, of the truncation of these columns by erosion could be detected. Their top portions have an "egg-beater" structure and are somewhat finer-grained probably because of greater mobility of the finer constituents of the sandy silt.

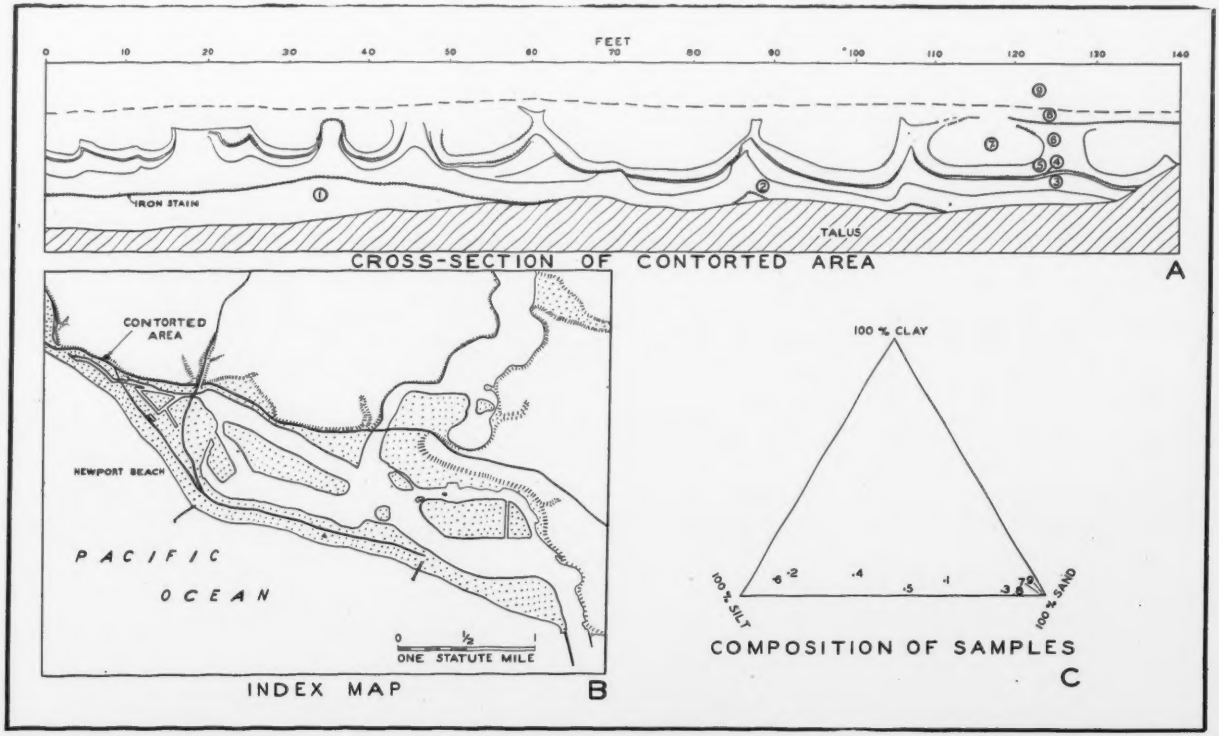


FIG. 1.—A, Sketch of folds exposed in cliff showing the variation in thickness of the beds involved and their relationship to each other. B, Location of contorted strata. C, Grain-size composition of samples collected at points indicated on cross-section (A).

FIG. 2.—Top: 100-foot length of section. Note absence of folds in the upper and lower beds.
Bottom: Lens of sand about seven feet long that is almost completely surrounded by the silt atop which it was originally deposited.

Mechanical analyses of the samples show a fairly clear grouping of the samples, with numbers 1, 2, 4, 5, and 6 very high in silt content and relatively poorly sorted, and numbers 3, 7, 8, and 9 clean well-sorted sands (fig. 1 and table 1). Minor amounts of secondary gypsum, present in all samples, were removed by treatment with dilute hydrochloric acid before the analyses were made. Calcium carbonate was absent or too rare to produce effervescence. Bulk densities, including the interstitial water, were measured for samples 5 and 7 by allowing the sediment to settle through water to form a layer made compact by tapping the container. The tests showed that the sandy silt (5) has a bulk density of 1.66 with a water content of 53 per cent by wet weight. This density is close to values of 1.59 and 1.61 obtained for two samples of silt collected from the present estuary. When it was originally deposited with the organic matter that now is gone, its density must have been even closer to that of the present estuary sediment. The overlying sand (7) had a bulk density of 1.86 with a water content of 45 per cent by wet weight, values well within the common range for saturated beach sands. Thus, the bulk density of the sand was originally about 15 per cent greater than that of the underlying sandy silt.

TABLE 1

Sample number	Median diameter (mm)	Sorting coefficient
9	0.340	1.27
8	0.100	1.29
7	0.170	1.30
6	0.028	1.53
5	0.063	1.53
4	0.036	2.54
3	0.120	1.26
2	0.029	1.84
1	0.079	1.34

CONCLUSIONS ON ORIGIN OF FOLDS

Numerous examples of interformational contortion have been reported in the literature and some of them have features in common with this one. Perhaps most similar are folds described by Beets (1946) in Miocene rocks of Italy, where lenses of sand occur above marl which forms columns separating them. Another sand layer, below the marl, is also deformed into cusps pointing upward into the gaps between the sand lenses above. Beets considered that the folds were produced when the top layer of sand started sliding on the marl, thereby producing an undulating surface. In the hollows of this surface more sand was later deposited, causing further settling of the sand lenses into the marl. Other excellent recent discussions of interformational folding have been presented by Fairbridge (1946) and Kuenen (1948), but their examples appear to require even greater lateral sliding than does Beets' example.

In view of the fact that there is no evident inclination of the columns of silt between the sand lenses at the Newport locality, it is believed that no lateral sliding occurred, but that the features can be fully explained by vertical sinking of the thick top layer of sand into the underlying sandy silt. Lithologically, the top sands (7, 8, and 9) and probably also the lower one (3), are similar to those on the present nearby open beach at Newport. The underlying sandy silts are well within the range of variation of silts found within the Newport Bay estuary and they were probably deposited as such. The author, therefore, considers that the sand (7) was deposited as a beach atop estuary silt. As the latter characteristically has a high water content and a correspondingly low specific gravity and high mobility, it tended to flow beneath the weight of the denser overlying sand. The easiest direction of movement, of course, was upward into the overlying sand through zones of weakness that developed probably by the separate sinking of blocks or sections of the sand. Probably the deformation occurred during the deposition of sand but

after several feet of it had accumulated. Deformation before consolidation is indicated by absence of slickensides or jointing as well as by lack of effect on the higher sands (8 and 9). Possibly, some of the silt even extruded at the ground surface and was buried beneath new sand, much of which may also have been deposited atop the sand lenses, further weighting and sinking them in the manner suggested by Beets.

These conclusions were based originally on lithology, but some support is provided by both paleontology and geomorphology. Fossils were found only in the sands above the contorted beds, beginning with sample number 9. One would expect from the foregoing that fossils in these sands should be open beach types, and such is chiefly the case. Lists of fossils reported from them by Bruff (1946) and Stevenson (1946) contain about 180 species. Only the more diagnostic genera from an ecological viewpoint will be mentioned here. Among the most abundant are *Donax*, *Tivela*, *Schizothaerus*, *Olivella*, *Conus*, and *Turritella*, all characteristic of open sandy beaches. In addition, there are abundant *Pecten latiauritus, var. monotimeris* and several species of *Calliostoma*. All of these forms live attached to kelp and thus, doubtlessly, were rafted to the beach, a common process on beaches fronting the open sea. Relatively rare specimens of *Ostrea*, *Mytilus*, and *Crepidula* are well-worn, perhaps indicating transportation by waves along the beach from a rock area, their characteristic environment of growth. Also present are some forms typical of lagoon muds, *Tagelus* and *Nassarius*. The latter are subordinate and may have been transported to the beach by ebbing tidal currents or by river floods, and then mixed with the dominant open beach forms. Higher in the section, near the top of the low cliffs, the lagoonal forms become more abundant and the sediment finer-grained, probably indicating a submergence and return to lagoonal conditions.

During the typical geomorphic cycle of both estuaries and lagoons (Johnson, 1938) a sand bar is formed that provides quiet water for deposition of marsh sediments or muds. As the cycle progresses, the bar is eroded on the seaward side and built up on the landward side, partly by washover fans and by wind action, until the sand comes to a position atop the lagoon or estuary fill. Eventually, if the cycle continues long enough both bar and fill are removed by erosion and a beach at the foot of a sea-cliff remains. Thus, it would seem a natural development for the beach sand to occur above the marsh sediment in the cliffs at Newport Beach.

REFERENCES

BEETS, C., *1946*. Miocene submarine disturbances of strata in northern Italy: *Jour. Geology*, vol. 54, pp. 229–245.

BRUFF, S. C., *1946*. The paleontology of the Pleistocene molluscan fauna of the Newport Bay area, California: *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, vol. 27, no. 6, pp. 213–240.

FAIRBRIDGE, R. W., *1946*, Submarine slumping and location of oil bodies: *Am. Assoc. Petrol. Geol. Bull.*, vol. 30, no. 1, pp. 84–92.

JOHNSON, D. W., *1938*. *Shore Processes and Shoreline Development:* John Wiley & Sons, Inc. New York, pp. 341, 376–382.

KUENEN, PH. H., *1948*. Slumping in the Carboniferous rocks of Pembrokeshire: *Geol. Soc. London Quart. Jour.*, vol. CIV, pt. 3, no. 415, pp. 365–385.

STEVENSON, R. E., *1946*. The paleontology and ecology of the Pleistocene fauna of the Newport Beach area, California: unpublished manuscript.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 116–117
JUNE, 1950

A SPOT TEST FOR PHOSPHORUS IN ROCKS

VIRGIL I. MANN
University of Wisconsin, Madison, Wisconsin

ABSTRACT

Acid ammonium molybdate will react with soluble phosphates to form a yellow precipitate. A technique has been devised which utilizes this principle to identify phosphorus-bearing minerals directly upon a rock surface.

The following procedure is a technique for location of phosphorus-bearing minerals on a rock surface. The two techniques most commonly used in phosphorus determination of rocks are both indirect. (See Feigl, 1946, p. 87.) The technique presented here depends upon a reaction taking place directly upon the mineral surface.

When a solution of acid ammonium molybdate reacts with a sufficient concentration of phosphate ions, a yellow solid of ammonium phosphomolybdate is precipitated. If a prepared solution of this reagent is applied under controlled conditions to the surface of most phosphorus-bearing minerals, the resulting precipitate forms a yellow film on the mineral. The precipitate is readily identified because of its color.

Most any solution of acid ammonium molybdate suitable for quantitative analysis may be used; however, such solutions have a tendency to decompose upon standing. In this respect the most satisfactory solution used to date is the one presented below. By preparing two separate solutions, a fresh reagent may be had when desired by mixing the two in proper proportions. The procedure for making the solution is as follows:

Solution 1. Dissolve 100 g of ammonium molybdate (C. P. grade) in 400 ml of water and 800 ml of 15 M ammonium hydroxide. Filter is necessary, though this seldom has to be done.

Solution 2. Mix 400 ml of 16 M nitric acid with 600 ml of water.

For use, mix the calculated amount of solution 1 with twice its volume of solution 2, adding solution 1 to solution 2 slowly, with vigorous stirring. (See Hodgman, 1946, p. 1337.)

The yellow precipitate of ammonium phosphomolybdate formed by this reaction is insoluble in alcohol and nitric acid, readily soluble in alkalies, but only slightly soluble in water. Although gallium, silicon, arsenic, and phosphorus will yield a precipitate under the conditions of this reaction, only arsenic will form a similar yellow precipitate If arsenic is suspected a simple "Marsh Test" will confirm or deny its presence.

Rock preparation requires a fresh break, or an otherwise clean surface. A flat surface generally yields the best results.

The selected surface is heated to about 60 degrees Centigrade. While the rock is at this temperature, the solution is applied by a capillary tube to the area to be studied. The area covered by the solution is washed with running water before it has a chance to dry. A characteristic yellow precipitate marks the areas where phosphate minerals are located. If desired a color control sample may be run on apatite.

The temperature to which the surface is heated varies, as the optimum temperature is a function of available phos-

phoric ion. As the acid both dissolves and oxidizes phosphorus, readily soluble or highly oxidized phosphates will react more rapidly at lower temperatures. Higher temperatures evaporate the solution to dryness, or in more extreme cases char the residue. The effect of higher temperature is to obscure mineral distribution.

The solution may be applied with a capillary tube. The tubing size depends upon the area to be studied. Too much solution tends to wash earlier formed precipitate into areas where no phosphorus-bearing minerals exist.

The reaction may be stopped whenever desired by washing the specimen with water from a tap. This will flush away excess precipitate in solution which has formed by ion diffusion. It will, however, leave the ammonium phosphomolybdate coating on the phosphorus-bearing minerals. The reaction should never be allowed to dry on the surface for reasons noted above.

The results of this test on highly permeable rocks have so far proved unsatisfactory.

ACKNOWLEDGMENTS

Appreciation is expressed to W. H. Twenhofel, and S. A. Tyler for constructive criticism of the manuscript.

REFERENCES

FEIGL, F., *1946. Qualitative Analysis by Spot Tests:* R. E. Oesper translation, Elsevier Pub. Co., New York.

HODGMAN, C. D., ed., *1946. Handbook of Chemistry and Physics:* 30th ed., Chemical Rubber Publishing Co., Cleveland, Ohio.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 2, PP. 118–119
JUNE, 1950

DISCUSSION

WHAT IS "SEDIMENTOLOGY"?

It is striking that in the report, in the April 1949 issue of this journal, on the meeting of sedimentary petrologists in London, the European participants spoke almost only of sedimentary petrology and petrologists while our American representative in discussing our work referred to "sedimentology," "sedimentologists" and "sedimentation."

It is difficult to explain the original adoption of this ugly hybrid inappropriate word and its present use in a report, in the *Journal of Sedimentary Petrology*, on a meeting aimed at forming an organization of sedimentary petrologists. Perhaps it came into use because the processes by which sedimentary rocks form are so much more accessible to study than those involved in the formation of igneous rocks; or because in the early days the concern was mainly with disintegrated sediments. However that may be, the proposal to form an organization of sedimentary petrologists is an indication that our science is outgrowing its adolescence and that we in America should assert our dignity as petrologists. We should no longer stand by humbly while the programs of geological societies take for granted that a section on petrology will deal only with igneous and metamorphic rocks. Actually the study of "sedimentation" is a part of the work of sedimentary petrologists only to the extent that the laboratory study of silicate melts is a part of the work of igneous petrologists. If we are to be designated sedimentologists let us at least demand that they call themselves igneologists.

The disadvantages to all concerned of resigning to them the right to dominate the title of petrologists come to a head in the field in which we meet—that of the study of metamorphic rocks. In an article in the *Bulletin of the Geological Society of America* for May (Vol. 61, No. 5) Billings reproaches students of metamorphic rocks for not giving more attention to the origin of metamorphosed sediments. Perhaps the sedimentary petrologist is himself to blame in that he has too largely surrendered his claims in that field.

MARCUS I. GOLDMAN
707 20th St. N. W.
Washington 6, D. C.

EDITORIAL NOTE

The use of the terms "sedimentology" and "sedimentologist" was suggested by Wadell in *Science*, in 1932. Twenhofel, in the *Report of the Committee on Sedimentation, 1930–1932*, stated that the terms had been rejected by the committee ten years earlier because they contain roots from two languages. "Sedimentation," for the process of formation, and "sedimentationist," for a student of sediments, were approved. No term for the *study* of sediments was discussed by Twenhofel. Wadell (1933) stated that since "terminology" itself is a Latin-Greek formation, there seems to be no reason for disqualifying "sedimentology." He pointed out that A. C. Trowbridge had listed "sedimentology" as one of his major fields, in *American Men of Science* some ten years earlier. "Sedimentationist" was considered objectionable as connoting an advocate or asserter of certain theories, comparing with "neptunist."

"Sedimentationist" has not been adopted widely, but "sedimentologist" is used frequently in the United States, as is "sedimentary petrologist."

The *Journal of Sedimentary Petrology* will welcome discussion of this question of terminology.

J. L. HOUGH

REFERENCES

TWENHOFEL, W. H., *1932*. Report of the Committee on Sedimentation, 1930–1932: *Nat. Research Council Bull.* 89, p. 18.

WADELL, H., *1932*. Sedimentation and sedimentology: *Science*, n. s., vol. 75, no. 1931, Jan. 1, 1932, p. 20.

———, *1933*. Sedimentation and sedimentology: *Science*, n. s., vol. 77, no. 2005, pp. 536–537.

Teaching Aids for Optical Mineralogy

Interference Figures of Crystals Under Polarized Light. A set of 41 color slides illustrating uniaxial and biaxial interference figures, determination of positive and negative figures and sections normal to an optic axis.
LX 25 Complete set of 41 slides with script, postpaid **$30.75**

Grain-Thin-Sections. A new development whereby one slide will possess several grains illustrating the complete optical character of the mineral.

Multiple Oriented Sections. 4 new slides:

Interference Figures	2 V Slide
Relief Scale	Bxa-Bxo Slide

WPS10 Complete set of 40 grain-thin-sections plus 4 multiple oriented sections ..... **$110.00** (list Roch. N.Y.)

(List of contents of LX 25 and WPS 10 free on request)

WARD'S NATURAL SCIENCE ESTABLISHMENT, INC.

3000 RIDGE ROAD EAST · ROCHESTER 9, N.Y.

Oceanographic Instruments

***SONIC SEDIMENTATION SAMPLERS, as designed by LaFond, Dietz, and Knaus.

***MECHANICAL SEDIMENTATION SAMPLERS, all patterns.
"Scoopfish" or Underway Sampler, cup type
Deep Sea Grab Sampled, Snapper type
Standard Snapper Samplers
Sediment Coring Devices, for cores 6" to 12'

***DREDGES, hand and power types, with removable sieves
***DEEP SEA REVERSING THERMOMETERS, all models
***REVERSING WATER BOTTLES
***CURRENT METERS, Mechanical and Electronic types
***WINCHES, Oceanographic, Hand and Power types
***UNDERWATER CAMERAS, for Lakes and Oceans
***SALINITY TESTING EQUIPMENT and TESTING SERVICES

We have established an international reputation as developers and fabricators of quality instruments for oceanographic research. Our glassblowing and electronic laboratories are staffed by unusually well qualified scientists and technicians. Our Chemistry Laboratory is headed by a qualified chemist with a good background in both chemistry and physics.

KAHL SCIENTIFIC INSTRUMENT CORP.
P.O. BOX 1166 EL CAJON (SAN DIEGO) CALIF.
Eastern Office: 50 West 3 St., New York 12, N.Y.

TESTING EQUIPMENT

For

SEDIMENTARY PETROLOGY LABORATORIES

Sample Splitters
Sieve Shakers

Electric Ovens
Balances

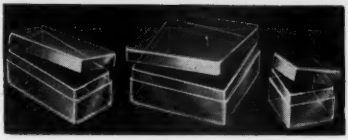
U.S. STANDARD SIEVES

Soil Dispersion Stirrers

—and equipment for petroleum, soil mechanics and concrete testing laboratories

HUMBOLDT MFG. CO.
MANUFACTURERS
2013 N. WHIPPLE STREET
CHICAGO 47, ILL.

TRANSPARENT BOXES



Offer maximum protection with complete visibility for samples, specimens of all kinds, small parts, etc. You will find innumerable uses for these unique, *transparent* boxes.

Five Sizes

Model				
A ($\frac{15}{16}$" x $\frac{15}{16}$" x $\frac{3}{4}$")	20 for $1; 100 for $ 4.60	D (3$\frac{1}{4}$" x 2$\frac{3}{4}$" x 1$\frac{1}{4}$")	5 for $1; 100 for $17.50
B (1$\frac{7}{8}$" x $\frac{15}{16}$" x $\frac{3}{4}$")	15 for 1; 100 for 5.60	E 6" x $\frac{7}{8}$" x $\frac{3}{4}$")	6 for 1; 100 for 16.00
C (1$\frac{7}{8}$" x 1$\frac{7}{8}$" x $\frac{3}{4}$")	12 for 1; 100 for 6.60	*(Postpaid if remittance accompanies order)*	

SAMPLE STORAGE SET

Store Key Samples for Quick Reference

Ten Model "A" Storage Sets store 1000 samples in 33 sq. inches of shelf space! Set consists of cork-capped or screw-capped vials in strong storage filing box, complete with labels and index cards! Thousands in use.

Model	*Vials*	*Capacity of Vials*	*Each Set*	*Dozen Sets*
A	100—4½" x ½"	10 ml	$3.25	$30.00
A-SC	100—4½" x ½"	10 ml	5.00	48.00
B	50—2¾" x ⅞"	15 ml	2.50	24.00
B-SC	50—2¾" x ⅞"	15 ml	4.50	48.00
C	50—3¾" x 1"	35 ml	3.50	36.00
C-SC	50—3¾" x 1"	35 ml	6.00	60.00

Index of Refraction Liquids

For the determination of index of refraction of minerals, rocks and other solid substances by the immersion method, by means of a microscope.

Shillaber's Certified Index of Refraction Liquids range from 1.400 to 1.700; intervals of 0.002; certified to plus or minus 0.0002 index. The index of these liquids will not change over a long period of time. The higher range of liquids extends from 1.71 to 1.83 index; intervals 0.01 index; liquids of higher index are in preparation.

Write for detailed list and prices. Just ask for leaflet 909.

Density Liquids

For determining the density of rocks and minerals by sink-and float methods.

Range: 1.1 to 5.0 density. Ready about April 15th, 1950. For full details write for Leaflet 908.

Shillaber's Immersion Oil

Has numerous advantages over cedar oil for use on immersion objectives for high power microscopy. Sample packet containing 2x1 ounce. $1.00 postpaid. Or, leaflet 909 will be sent on request.

Chemical Microscopy Sets

For use with Chamot and Mason's Handbook of Chemical Microscopy Vol. 1 and 2. Leaflet 913 on request.

R. P. CARGILLE

118 Liberty Street **New York 6. N.Y.**

Please mention the *Journal of Sedimentary Petrology* when writing to advertisers.

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

SOCIETY OFFICERS (APRIL, 1950-APRIL, 1951)

President: WILLIAM C. KRUMBEIN, Evanston, Illinois

First Past-President: H. B. STENZEL, Austin, Texas

Second Past-President: R. DANA RUSSELL, San Diego, California

Vice-President: GORDON RITTENHOUSE, Cincinnati, Ohio

Secretary-Treasurer: CECIL G. LALICKER, Dept. of Geology, University of Kansas, Lawrence, Kansas

Editor: W. H. TWENHOFEL, Orlando, Florida

Managing Editor: J. L. HOUGH, University of Illinois, Urbana, Illinois

PACIFIC SECTION OFFICERS (1950–1951)

President: MERLE ISRAELSKY, Padadena, California

Secretary-Treasurer: HARRY R. TURVER

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

ASSOCIATION OFFICERS (APRIL, 1950-APRIL, 1951)

President: C. L. MOODY, Shreveport, Louisiana

Past-President: C. W. TOMLINSON, Ardmore, Oklahoma

Vice-President: JOHN EMERY ADAMS, Midland, Texas

Secretary-Treasurer: HENRY N. TOLER, Southern Natural Gas Co., 1510 Deposit Guaranty Bank Bldg., Jackson, Mississippi

Editor: ALFRED H. BELL, Illinois Geological Survey, Urbana, Illinois

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN